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**IMPROVING NAVAL SHIPBUILDING PROJECT
EFFICIENCY THROUGH REWORK REDUCTION**

by

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September 2007

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ABSTRACT

The rising cost of U.S. Naval Ships and the rate of change in technology require a thorough analysis of current shipbuilding practices. The Navy wants the latest and greatest technology, while at the same time keeping overall cost low. Some technologies are obsolete before completion of the ship's design and construction. A design locked in at Critical Design Review (CDR) undergoes multiple modifications prior to ship's delivery. Design changes drive up cost. The goal is to provide the Warfighter Battlespace Dominance while keeping cost low enough to allow a consistent purchase of additional ships.

To accomplish this goal, both industry and the Navy must be aware of what is driving design changes and willing to revise existing practices. The objectives of this thesis are to identify the major sources of rework and to suggest modifications and improvements to existing practices. A review of DoD Acquisition and the Shipbuilding process identifies design changes resulting from requirements volatility, inconsistent execution of Defense Acquisition, and the rigidity of the design and construction process as major sources of rework. Recommendations include improving change management, optimizing the schedule for resilience, and the use of a modular open systems approach to reduce rework.

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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	Analysis of Alternatives
APB	Acquisition Program Baseline
ASN RDA	Assistant Secretary of the Navy for Research Development & Acquisition
CAD	Computer Aided Drafting
CBO	Congressional Budget Office
CDD	Capability Development Document
CDR	Critical Design Review
CM	Configuration Management
CPD	Capability Production Document
CPM	Critical Path Method
DP/CPF	Defense Procurement for Cost Pricing and Finance
DRR	Design Readiness Review
DoD	Department of Defense
DoDD	Department of Defense Directive
DoDI	Department of Defense Instruction
DOT	Department of Transportation
DT&E	Developmental Test and Evaluation
ECP	Engineering Change Proposal
EDM	Engineering Development Models
FOC	Full Operational Capacity
FOT&E	Follow on Operational Test and Evaluation
FRP	Full Rate Production
GAO	Government Accountability Office
GFE	Government Furnished Equipment
GFI	Government Furnished Information
GT	Group Technology
HBCM	Hull Block Construction Method
ICD	Initial Capabilities Document
IOC	Initial Operational Capacity
IOT&E	Initial Operational and Evaluation
KPP	Key Performance Parameters

LFT&E	Live Fire Test and Evaluation
LRIP	Low Rate Initial Production
MDA	Milestone Decision Authority
MOSA	Modular Open Systems Approach
NAVSEA	Naval Sea Systems Command
N/C	Numerical Control
OA	Operational Assessment
ORD	Operational Requirements Document
OT&E	Operational Test and Evaluation
PC	Production Control
PDR	Preliminary Design Review
PEO	Program Executive Offices
PERT	Program Evaluation and Review Technology
PM	Program Manager
PRR	Production Readiness Review
PWBS	Product Oriented Work Breakdown Structure
RFP	Request for Proposal
ROM	Rough Order of Magnitude
SARS	Selected Acquisition Report Summaries
SD	System Demonstration
SDD	System Development and Demonstration
SI	System Integration
SNAME	The Society of Naval Architects and Marine Engineers
SWBS	Ship Work Breakdown Structure
T&E	Test and Evaluation
TDS	Technology Development Strategy
TRL	Technology Readiness Level
VFI	Vendor Furnished Information
WBS	Work Breakdown Structure
ZOFM	Zone Outfitting Method
ZPTM	Zone Painting Method

GLOSSARY

Accuracy Control – The use of statistical techniques to monitor, control and continuously improve shipbuilding design details and work methods to maximize productivity (Storch, 1995).

Critical Path Method – Scheduling methodology that determines which sequences of tasks within a project requires more time to accomplish than others based on the duration and relationships of all task in the project.

Downhand – Position of welding wherein welding is accomplished from the topside and the axis of the weld metal is horizontal (Storch, 1995).

Group Technology – The logical arrangement and sequence of all facets of a company operation in order to bring the benefit of mass production to high variety, mixed quantity production (Storch, 1995).

Hull Block Construction Method – Hull parts, sub-assemblies and blocks are manufactured in accordance with the principles of group technology (Storch, 1995).

Interim Product – An assembly or portion or work which can be logically scheduled and managed as though it were a deliverable product (unit, block, assembly, sub-assembly, etc) (Storch, 1995).

One-off product – a product made to a client specification, which is unique and not replicated or mass produced (Storch, 1995).

Palletizing – The act of collecting and grouping materials together to match a material list by system (MLS) (Storch, 1995).

Problem Area – A division of the production process into similar types of work problems, which can be by feature, quantity, quality or kind of work.

Stage – A division of the production process by sequences, such as sub-steps of fabrication, sub-assembly, assembly, erection, outfitting on-unit, outfitting on-block and outfitting on-board (Storch, 1995).

System - A structural or operational characteristic such as longitudinal or transfer bulkheads, deck lighting system, piping system, etc.

Zone – A geographical division of the product such as an engine room, cargo hold, etc.

Zone Outfitting Method - Concurrent hull construction and outfitting by providing precise zone by stage control for which there are three basic stages: on-unit, on-block and on-board outfitting and a sub-stage for downhand outfitting on overheads when blocks are upside down (Storch, 1995).

Zone Painting Method – Surface preparation and coating treated as an integrated aspect of the overall construction process (Storch, 1995).

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I. INTRODUCTION

A. BACKGROUND

The rising cost of U.S. Naval Ships and the rate of change in technology require a thorough analysis of current shipbuilding practices. The Navy wants the latest, most effective, technology while at the same time keeping overall cost low. Some technologies may become obsolete before a ship can be designed and constructed. A design locked in at Critical Design Review (CDR) is likely to be modified multiple times prior to ship's delivery. Design changes drive up cost, but not changing the design may result in delivery of a new ship with outdated technologies. The goal is to provide, to the Warfighter, battle space dominance while keeping the overall cost low enough to allow a consistent purchase of additional ships.

To accomplish this goal, both the shipbuilding industry and the Navy must be aware of design change drivers and be willing to revise existing practices. A review of the current ACAT I ship programs listed on the Department of the Navy Research, Development & Acquisition website shows that most programs involve procurement of multiple ships. Multi-ship procurement is considered a cost saving method because it allows use of "Economic Order Quantity" material purchases and reaps the benefits of shipbuilder's lessons learned and the learning curve effect. But, if ship design is locked down at Critical Design Review (CDR), and it takes five to seven years to build a ship, then it is obvious that design modifications are inevitable if the desire is to prevent delivery of obsolete technology.

Ship design and construction consists of multiple tasks that feed other tasks in a highly complex and interdependent flow. The physical location of compartments and equipment dictates, to some degree, when they should be constructed. Disruption in the order of sequenced work tasks often causes rework and reduced productivity. The ship specifications and other documents provided at the beginning of the shipbuilding contract are vital to supporting these scheduled tasks. If information is missing or ambiguous,

design and construction involving the related area may be delayed. Construction in unaffected areas continues at the original scheduled pace. The result is out of sequence work.

On the other hand, if the specifications and other documents provided at the beginning of the contract are expected to support the design and construction of multiple ships, the result would be a new ship with obsolete technology. Immediately after delivery, the ship would undergo a technology refresh involving the rip-out and replacement of the ship's initial systems. Where is the cost savings in that? Finding new methods for dealing with out of sequence work must be explored, but that alone will not be enough. Even if multi-ship procurement offsets the cost of out of sequence work and replacement of obsolete technology, the waste of manpower and material still needs to be addressed. Acquisition methods preserving the benefits of multi-ship procurement without causing rework are needed. Improvements in these two areas would provide a cost savings and prevent the waste of delivering and then replacing obsolete technology.

B. PURPOSE

The research investigates the implementation of Department of Defense (DoD) acquisition practices in Naval Shipbuilding Projects, in particular, the development of requirements leading to design and construction. Experience and research demonstrate the negative impact of changing requirements, sub-optimal design activity sequencing, and production identified defects. Theoretical costs are quantified and alternatives analyzed. The objective is the development of modifications and improvements to existing acquisition and shipbuilding practices.

C. RESEARCH QUESTIONS

The implementation of DoD acquisition practices in Naval Shipbuilding Projects, in particular, the development of requirements leading to design and construction, directly affects the follow on design and construction activities. The following questions were addressed in order to understand the issues:

1. What are the major causes of rework?
2. How can requirements volatility and associated rework be reduced?
3. How can the quantity and cost of design changes after start of detail design and construction be reduced?
4. How to provide the latest and greatest technology without incurring the high cost of out of sequence work?
5. Is it more cost effective to proceed with an unstable design or delay the start of design and construction?
6. Is it more cost effective to use an event driven or schedule driven process?

D. BENEFITS OF STUDY

This thesis demonstrates the elasticity of the current DoD/Shipbuilder approach to design and construction as well as the effects of changes. The information identifies the potential for process improvement and cost savings.

E. SCOPE AND METHODOLOGY

The thesis analyzes Naval Shipbuilding projects from Milestone A, technology demonstration, through system development, construction, and delivery. The emphasis is on the time phasing of project and contractor activities and their effects. The expected maturity of each step in the process is analyzed for leading indicators of follow-on performance. The thesis targets opportunities created by current acquisition guidance, practices, and behaviors.

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II. OVERVIEW OF NAVAL SHIP ACQUISITION

A. INTRODUCTION

U.S. Navy ship acquisition is a complex activity undertaken over extended periods. The number and extent of issues influencing the results of ship acquisitions is enormous. Consider the billions of dollars in funds, the interests of the public, their representatives, contractors, their shareholders/employees, Navy leadership, and Warfighters. There is no end to the permutations of programs and performance.

This variety of interests is synthesized with DoD acquisition management rigor to create the programs of today and the future. It is important to view the DoD acquisition model with a mind open to the effects of all the related interests and their varying power to influence outcomes.

PEO Ships is the largest of five Program Executive Offices (PEO). The PEO Ships Web site provides a good overview of how they manage the acquisition of non-nuclear U.S. Navy surface vessels, excluding aircraft carriers (<http://peoships.crane.navy.mil/program.htm>). In addition to acquisition, they manage full lifecycle support for in-service vessels. Their responsibilities include research and development, acquisition, systems integration, construction, lifetime support and in some cases deactivation and disposal.

PEO Ships reports directly to the Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN RDA) regarding acquisition management and to the commander of the Naval Sea Systems Command (NAVSEA) regarding support for in-service vessels. The DoD 5000 Series Directives provide the direction for implementing and progressing through the Defense Acquisition Lifecycle. The Defense Acquisition Management Framework, established by DoD Instruction Number 5000.2 (DoDI 5000.2), consists of the Milestones, Phases, and Efforts used to determine a program's status and readiness to progress to the next stage of development.

The DoD acquisition model formalizes the path from the recognition of a military need through the eventual disposal of those systems that fulfill that need. It is not a guarantor of technical success, though it delivers best practice approaches to improve the probability of success by programmatic and technical means. The process review is necessary to see the potential for modifications to enhance ship acquisition performance, with its peculiar demands.

B. REVIEW OF DOD ACQUISITION PROCESS MODEL

The Defense Acquisition Management Framework spans the lifecycle of the program from concept development to disposal. The framework is divided into Pre-Systems Acquisition, Systems Acquisition, and Sustainment. All three activities have been explored briefly, but the research concentrated on the activities commencing after Pre-Systems Acquisition. As shown in Figure 1, these three activities are further broken down into five phases: Concept Refinement; Technology Development; System Development & Demonstration; Production & Deployment; and Operations & Support (DoDI 5000.2, 2003). Each phase has entrance and exit criteria, with most requiring action from the Milestone Decision Authority (MDA).

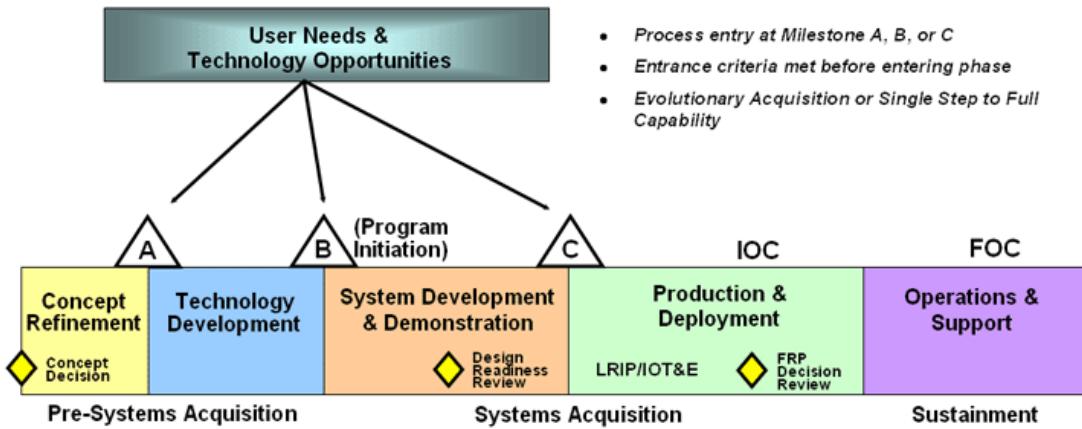


Figure 1. The Defense Acquisition Management Framework (From: DoDI 5000.2, 2003)

1. Concept Refinement Phase

The purpose of the Concept Refinement Phase is to refine the initial concept outlined in the Initial Capabilities Document (ICD) and to develop a Technology Development Strategy (TDS) for guidance through the next phase. The ICD guides the effort in this phase, as well as the initial efforts in the Technology Development Phase. The entrance to this phase depends on an approved ICD, an approved plan for conducting an Analysis of Alternatives (AoA), and phase funding. The phase exits upon Milestone Decision Authority (MDA) approval of a preferred solution and the TDS (DoDI 5000.2, 2003).

2. Technology Development Phase

The Technology Development Phase focuses on reducing the technology risk. An iterative approach is implemented to develop and evaluate technologies to satisfy the system requirements. This phase begins after the Milestone A decision approving the TDS. The goal of using the AoA is to determine the appropriate technologies to address, the capabilities identified in the ICD within a reasonable amount of time. The phase exits after the demonstration of an affordable increment of militarily useful capability in a relevant environment. As previously noted, the system must also be capable of being developed in a short timeframe. The Capability Development Document (CDD) is a product of the Technology Development Phase. The Acquisition Program Baseline (APB) and CDD establish the Key Performance Parameters (KPPs) used throughout the ensuing program to measure system performance. The technology development phase may also coincide with ship program initiation to permit concurrent design activities (DoDI 5000.2, 2003).

Configuration management of the developing functional design and allocated baselines rises in formality, as their maturity is determined during reviews. This phase provides the opportunity to manipulate and change significant system conceptual design approaches. Changes are expected and used to balance performance, functionality, cost,

etc. These changes may be viewed generally as strategic, so while implementing them in the baseline may not be challenging, they can have profound effects on the downstream design cost, schedule, and performance.

3. System Development & Demonstration (SDD) Phase

The System Development & Demonstration Phase consists of the System Integration (SI) and the System Demonstration (SD) efforts. This phase begins after approval of Milestone B and starts the System Acquisition activities. The selected technologies are presented in the preliminary design effort. The design is matured through Preliminary Design Review (PDR), to Critical Design Review (CDR), and ultimately Production Readiness Review (PRR). SI begins during preliminary and critical design periods (DoDI 5000.2, 2003).

The SI effort involves integrating demonstrated subsystems and components in an effort to reduce risk. The entrance criteria require a technical solution comprising subsystems that have not yet been integrated into a complete system, phase funding, and an approved CDD. The integration activities typically include demonstration of prototype articles or Engineering Development Models (EDMs). Demonstration of prototypes or EDMs in a relevant environment, documentation of the system configuration, and a successful Design Readiness Review (DRR) are required prior to exiting this phase (DoDI 5000.2, 2003).

Successful completion of the DRR starts the SD effort, leading to the PRR and Milestone C. The SD effort demonstrates the ability of the system to operate in a useful manner consistent with the approved KPPs. The entrance criterion requires successful demonstration of the system in prototypes or EDMs. The demonstration activities include Developmental Test & Evaluation (DT&E), Operational Assessment (OA), Operational Test & Evaluation (OT&E), and preliminary Live Fire Test & Evaluation (LFT&E). The exit of the SD effort depends on the demonstration of the system using prototypes or EDMs in its intended environment; satisfactory measurement of the system's performance against the KPPs; reasonable availability of industrial capabilities; and the determination that the system meets or exceeds exit criteria and Milestone C entrance

requirements. The flexibility of the framework allows a program to enter the acquisition cycle in either SI or SD with the successful completion of Milestone B (DoDI 5000.2, 2003).

During SDD, the design is maturing and configuration management (CM) of the requirements and specifications is formalized. Formal CM of the specifications is critical to demonstrating a stable design that will satisfy Milestone C requirements. At the same time, there is an expected capacity to identify needed changes or accept proposed improvements. Proposed changes, at this stage, directly affect cost, schedule and performance. The program employs technical and programmatic processes to evaluate these impacts and make appropriate decisions.

4. Production & Deployment Phase

The approval of Milestone C starts the Production and Deployment Phase, and represents the decision to commit the program to production. The purpose of the Production & Deployment Phase is to achieve the specified operational capability. Depending on requirements, authorization is for Low Rate Initial Production (LRIP), production, or procurement. If LRIP is required, a subsequent review and decision is needed to authorize full-rate production (FRP).

Depending on the LRIP requirement, and if Milestone C is the program initiation, entrance factors may include: satisfactory performance in DT&E and OA; mature software capability; elimination of significant manufacturing risks; controlled manufacturing processes; an approved ICD; an approved Capability Production Document (CPD); acceptable interoperability; acceptable operational supportability; demonstration of system affordability throughout the life cycle; optimal funding, and phased rapid acquisition. LRIP for ships is production of items at the minimum quantity and rate feasible to sustain the production base. If LRIP is required, a Full-Rate Production Decision Review is conducted to consider the results of the IOT&E and LFT&E (if applicable); interoperability demonstrations; supportability demonstrations; cost and manpower estimates; and supportability and certification of command, control, communications, computer and intelligence (if applicable) (DoDI 5000.2, 2003).

The Full-Rate Production and Deployment portion of the Production and Deployment Phase starts with the authorization given upon a favorable Full-Rate Production Decision Review. Focus is on producing and delivering the system to the field for operational use. Program Management oversight must insure the fielded system meets the user's requirements specified in the CPD and that the system is produced at an economical rate. Follow-on Operational Test and Evaluation (FOT&E) may be conducted to assess the system's operational effectiveness and suitability. Correction of deficiencies should be demonstrated as well. Since fielding of the first system starts the Operations and Support Phase, these two phases overlap (DoDI 5000.2, 2003).

As in the SDD phase, proposed changes directly affect cost, schedule, and performance. After production and procurement start, the effects are magnified. The further along in production, the more risk a change will create excessive impacts due to waste, rework, and rescheduling (Storch, Hammon, Bunch, & Moore, 1995).

5. Operations & Support Phase

Full Operational Capability (FOC) is achieved during the Operations & Support Phase. Logistics and operational readiness are the main focus of this phase. Supportability is provided over the life of the system. This includes monitoring the system status to ensure the user's needs are still being met. The Operations & Support phase is divided into Sustainment and Disposal (DoDI 5000.2, 2003).

The Sustainment portion starts immediately upon fielding or deployment of the first system. Its purpose is to provide the necessary supplies and services to maintain operational readiness and operational capabilities. Activities include executing operational support plans, conducting modifications and upgrades to hardware and software, and measuring customer satisfaction (DoDI 5000.2, 2003).

The end of a ship's useful life results in decommissioning and in some cases transfers or sales to friendly foreign navies. If a ship is not transferred or sold, it must be properly disposed of to ensure DoD compliance with environmental, safety, security, and

health requirements. The activities required to demilitarize and dispose of the system are managed in the Disposal portion of the Operations and Support Phase (DoDI 5000.2, 2003).

C. CHAPTER SUMMARY

The DoD acquisition process provides a roadmap for following the evolution of a ship concept into design and, ultimately, construction and delivery. The relationship of the design to the program and construction status is the basis for an analysis of potential issues related to design volatility and its effect on cost and schedule. So far, the description is of the high-level DoD acquisition model. Grasping the intent of the model is critical to understanding the relationship between the volatility of design maturity to cost and schedule impacts.

From Milestone A until delivery, there is a continuum of design development and maturation into which changes, or corrections, appear to have an ever-increasing direct effect. In addition, the early period holds the potential for significant downstream impact. Of particular interest is the relative consequence of volatility to the acquisition process, both technically and programmatically.

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III. OVERVIEW OF SHIPBUILDING PROCESS

A. INTRODUCTION

Shipbuilding utilizes highly complex processes to design and construct built-to-order products that meet customer requirements. This requires continuous interaction between the customer, the shipyard, suppliers, and governing bodies. The shipbuilding process involves concurrent design, engineering, planning, scheduling, and manufacturing throughout the entire project. As such, coordination of all activities is critical to successful on time, and within budget completion.

Knowing the dependencies of these tasks is critical to managing the project. The effects of design changes grow over time. Even though these effects are greatest during the construction phase, this chapter reviews all stages starting with the pre-contract activities: preliminary concept design, contract design and bidding/contracting. A more detailed review of the shipbuilding management cycle follows explaining the activities after contract award. Group Technology, as applied to shipbuilding, is the management approach presented.

B. PRELIMINARY-CONCEPT DESIGN

Preliminary-Concept Design analyzes and defines basic requirements in response to the customer's needs or perceived needs. The work breakdown structure (WBS) used during this time is systems oriented. The primary activities are the control and development of ship design through drawing and document development and design verification. Outputs of the preliminary-concept design define the contract design baseline.

Preliminary design decomposes performance requirements into the appropriate level of physical or functional abstraction. The architecture of the requirements, specifications, and related systems are developed. An example is mobility. A speed requirement is a partial decomposition of the system's mobility needs. The speed

requirement is then decomposed, or allocated, to the hull form and the propulsive force needed to achieve required speed. This is a concurrent architecture development of the need for propulsion and hull design. The requirements decomposition continues until the specification is developed.

In the example, a specification may be “the ship shall have two prime movers of XXX horsepower each.” Alternatively, “the hull form shall have less than XXX resistance to motion in sea state 0.” The Critical Design Review locks in the ship specifications and requirements in the form of the contract data package.

C. CONTRACT DESIGN

Contract Design includes the preparation of drawings and specifications required to provide sufficient information for bid development, contract negotiation and the start of ship detail design. The contract documents depict the contractual configuration for the procured ship and listings of additional guidance documents required for development of the detail design drawings. Examples of the additional documents or information include the following:

Schedule A – A listing of Government Furnished Equipment (GFE), by system, including quantity and delivery dates.

Schedule C – A listing of Government Furnished Information (GFI), by system, including drawing numbers, drawing revisions and delivery dates.

GFI provides the detailed information needed for developing the detail design drawings in the case of GFE. Vendor Furnished Information (VFI) provides the detail for vendor furnished equipment. The combination of contract documents and GFI/VFI provide the detail required for detail design. Any changes to these documents after contract award constitutes design change and may be subject to a cost and or schedule adjustment.

D. BIDDING/CONTRACTING

Using the contract documents and the provided delivery dates for milestones and GFI/GFE, the shipyard develops a response to the Request for Proposal (RFP).

Specification of equipment and requirements provide a basis for cost estimations. The contract price is decided and vessel delivery dates are established. This requires close coordination between the project development team, cost estimation team, planning, and supply chain management.

Preliminary planning occurs between the bidding process and contract award. At this time, dates for major events such as start fabrication, lay keel, launch, and delivery are established. In addition, development of a preliminary build strategy provides construction guidelines and becomes the basis for detail design, preliminary production schedules, and resource allocations. Planning is heavily involved in this stage of the process and is responsible for estimation of production hours and time. The estimates reflect shipyard facility capacities, existing production workloads/schedules, and availability of facility lay down space.

E. THE MANAGEMENT CYCLE

The management cycle in the shipbuilding process starts with estimating, and then moves into the planning, scheduling, execution and evaluation phases. The transitions displayed in Figure 2, illustrate the need for both a systems and product or zone oriented grouping in the work breakdown structure (Storch, 1995). The cycle starts out using a systems orientation for estimating and early planning (including design). It then transitions to a zone orientation for additional planning, scheduling, execution, and initial testing. Another transition is required to provide a systems view for the overall test and evaluation. This transitional approach is the basis for group technology in the shipbuilding process.

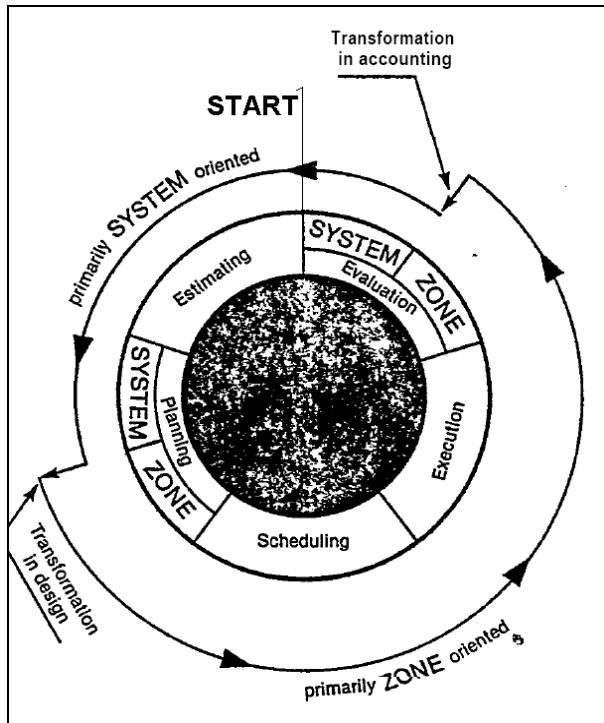


Figure 2. System and Zone Orientation in Management Cycle (From: Storch, 1995)

F. GROUP TECHNOLOGY

The actual construction involves many interrelated tasks that start with converting raw materials, such as steel, into interim products. These interim products are then available for use in the next higher assemblies. Each task depends on the proper execution of the relevant preceding tasks. The management approach employed by the shipyard determines the division and grouping of tasks. One example is Group Technology (GT).

GT is a method for managing industrial processes using an efficient “classification and coding system” (Storch, 1995). The philosophy is to divide the product, based on the classification criteria, into smaller, manageable, interim products. The resources, including personnel, and the processes required to produce the interim product make up a “cell” (Storch, 1995). These interim products are then combined “to make a new larger product” (Shenoi, 2006).

The classification and coding system used determines division of work in development of an interim product. Two such systems are the Ship Work Breakdown Structure (SWBS) and the Product-Oriented Work Breakdown Structure (PWBS). GT applied to shipbuilding uses both, depending on the stage in the management cycle. This section explains the differences between the two and their relationship to the management cycle. It starts by explaining GT, and then addresses a shipbuilding approach that involves integration of hull construction, outfitting and painting.

The SWBS is a systems-oriented structure used by the Navy. It breaks down the ship into functional systems. Prior to the decline in shipbuilding, the SWBS was the primary classification and coding system used throughout the lifecycle of the ship. Tasks requiring a systems view such as estimating, preliminary design, and overall test and evaluation still use the SWBS. However, the structure defined by the PWBS more accurately reflects the actual production of the ship. Figure 3 shows a shipbuilding classification and coding system based on the SWBS.

FIRST DIGIT		SECOND DIGIT																
BASED ON US NAVY SWBS		FIRST DGT	1	STRUCTURE	2	PROPULSION MACHINERY	3	ELECTRICAL	4	COMMAND & COMMUNICA- TION	5	AUXILIARY MACHINERY	6	OUTFIT	7	ARMAMENT	9	SHIP ASSEMBLY & SUPPORT
0	STRUCTURE	0	PLATE	CONTROLS	GENERATORS	SAFETY & SECURITY	NAC			HULL MARKING							STAGING	
1		1	SECTION	ENERGY GENERATOR	MOTORS	COMMAND & CONTROL	SALT WATER SYSTEMS			SHIP FITTINGS	GUNS & AMMUNITION						TEMPORARY SERVICES	
2		2	SUB-ASSEMBLY	PROPULSION UNITS	TRANSFORMERS	NAVIGATION	FRESH WATER SYSTEMS			COMPARTMENT-ATION	MISSILES & ROCKETS						MATERIALS HANDLING & REMOVAL	
3		3	ASSEMBLY	TRANSMISSION	SWITCHBOARDS	INTERIOR COMMUNICATIO N	FUEL SYSTEMS			PRESERVATION & COVERINGS	MINES						CLEANING SERVICES	
4		4	FOUNDATION	PROPELLOR	CONTROLLERS	EXTERIOR COMMUNICATIO N	A O SYSTEMS			LIVING SPACES	DEPTH CHARGES						HOLDS & TEMPLATES	
5		5	CASTINGS	PROPULSION SUPPORT	PANELS	SURFACE SURVEILLANCE	AIR, GAS & MISC. FLUID SYSTEMS			SERVICE SPACES	TORPEDOES						FIGS & FIXTURES	
6		6	FLAT PANEL	FUEL & L O SUPPORT	CABLE	UNDERWATER SURVEILLANCE	SHIP CONTROL			WORKING SPACES	SMALL ARMS & PYROTECHNICS						LAUNCHING	
7		7	CURVED PANEL	AUXILIARY PROPULSION	LIGHTING	COURIER-MEASURES	RASIFAS			STOWAGE SPACES	CARGO MUNITIONS						DRYDOCKING	
8		8	HULL MODULE	OPERATING FLUIDS		WEAPON CONTROL	MECHANICAL HANDLING				AIRCRAFT RELATED WEAPONS						TESTS	
9		9	DECKHOUSE MODULE	SPARE PARTS	SPARE PARTS	SPARE PARTS	SPARE PARTS			SPARE PARTS	SPARE PARTS						SPARE PARTS	

Figure 3. Shipbuilding Classification and Coding System (From: http://www.sesnet.soton.ac.uk/degpro/SESS2002/SESS2002_lecture_notes.htm)

GT supports production activities by using the PWBS for the classification and coding system. Parts are procured, fabricated and then joined together to create interim parts or subassemblies during the production stages of the ship. GT provides all of the resources required, including personnel, to complete a subassembly without concern for functional systems. Production of various subassemblies occurs simultaneously. These subassemblies are then grouped with the tasks and resources required to build the next higher subassemblies and so on. This grouping continues until all interim products are integrated, presenting a complete ship. The lowest level of these interim products is a zone.

Shipbuilding consists of many tasks that require construction processes as opposed to manufacturing processes. Many interim products are one or few of a kind. GT uses the PWBS to realize some of the benefits a manufacturing company realizes with mass production by identifying “relative permanency of location and function, moving work to the worker, balanced product flow, etc.,” (Storch, 1995). The idea is that an efficient classification system provides a tool that makes it easier to organize the required resources, thereby increasing productivity.

GT reduces the amount of inventory for in-process work by arranging work areas into cells. Cells are scheduled and loaded with parts based on the classification criteria. Shapes, material and size, among others, are all attributes used in defining a cell. Setting up cells to produce interim products based on similar criteria reduces the amount of handling required for parts, as well as, the amount of setup time required for various machines used throughout the production process (Storch, 1995).

With the decline in shipbuilding, it was determined that the SWBS and other such systems lacked the ability to organize work in a manner conducive to the actual production process (Todd Shipyards, 1986). Work packages derived from a system function did not provide a clear division of work between fabrication and assembly processes. In addition, many of the shipboard systems typically spanned a vast area of the ship. This made production control and monitoring easier said than done (Todd Shipyards, 1986). Group Technology, as applied to shipbuilding, uses both the SWBS and the PWBS to manage the shipbuilding processes.

The PWBS utilizes a combination of product description (material type, quantity, location, size, etc.) and product control attributes (fabrication, assembly, erection techniques, etc) for classification and coding. Division of attributes for interim products falls into the following five basic categories and provides the basis for the six-character PWBS code (Todd Shipyards, 1986):

Work Type – Identifies work required for a given interim product. (1st – character)

Manufacturing Level – Identifies work sequence for a given work type. (2nd – number)

Zone Type – Identifies production objective within a given manufacturing level. (3rd – number)

Problem Area – Identifies work requirements within a given zone. (4th/5th – number)

Stage – Identifies work sequence for a given problem area. (6th – number)

Reviewing an approach that applies the PWBS classification and coding system provides an understanding of how GT relates to shipbuilding. The approach divides the initial shipbuilding process into three distinct work types: Hull Block Construction Method (HBCM), Zone Outfitting Method (ZOFM), and Zone Painting Method (ZPTM). Further sub-division defines fabrication and assembly processes.

Classification Trees or the PWBS Classification and Coding book provide the source for selecting the appropriate code for each of the five basic categories. The process produces a six-character code used to identify and describe interim products. Once accomplished, resources required for interim products are identified. Required resources include material, manning, facilities location for manufacturing process, equipment and tools required for task assignments, transportation to move interim product to the next stage of production, overhead support such as material runners to deliver required materials to assigned workstations (Storch, 1995).

Figures 4, 5, 6, and 7 provide examples of the classification trees used in the development of work packages (U.S. Department of Transportation [DOT] Maritime Administration, & Todd Pacific Shipyards Corporation, 1986). The PWBS Classification Tree, figure 4, illustrates the initial breakdown of distinctive work types for parts and/or interim products in the shipbuilding process.

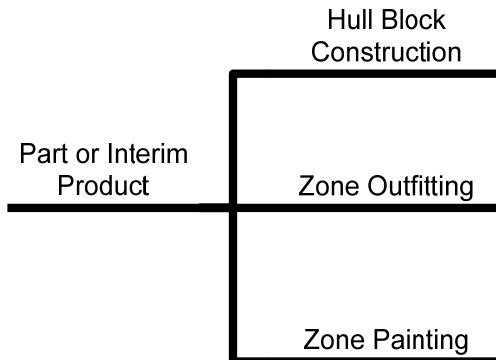


Figure 4. PWBS Classification Tree (After: <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA452827&Location=U2&doc=GetTRDoc.pdf>)

The Hull Block Construction Method (HBCM) divides the shipbuilding system into production blocks that have the same or similar type work and utilizes the same work process. The goal is to divide the ship system into workable units that maximize outfitting and painting of units (blocks) prior to hull erection. Figure 4 shows the HBCM Classification Tree used to derive the PWBS classification and coding for work types designated as HBCM (DOT, 1986). Zone Outfitting and Zone Painting use the same logic as the Hull Block Construction Methods by organizing outfitting and painting processes by zone and staging the work into on-unit, on-block and on-board work packages. Figures 5 and 6 show the ZOFM and the ZPTM Classification Trees respectively (DOT, 1986). Using Group Technology with the PWBS Classification and Coding allows for maximum productivity throughout the overall construction process.

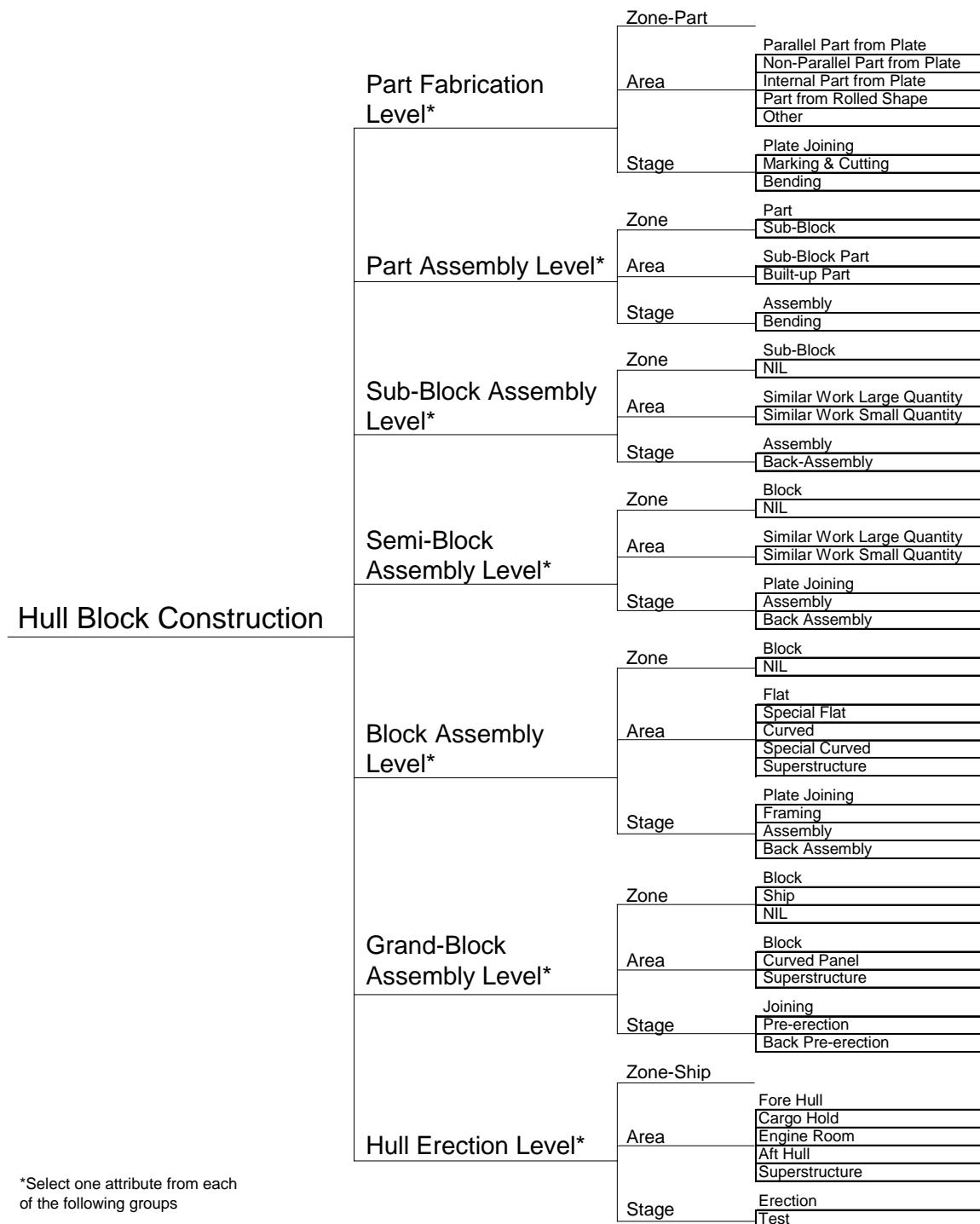


Figure 5. HBCM Classification Tree (After: <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA452827&Location=U2&doc=GetTRDoc.pdf>)

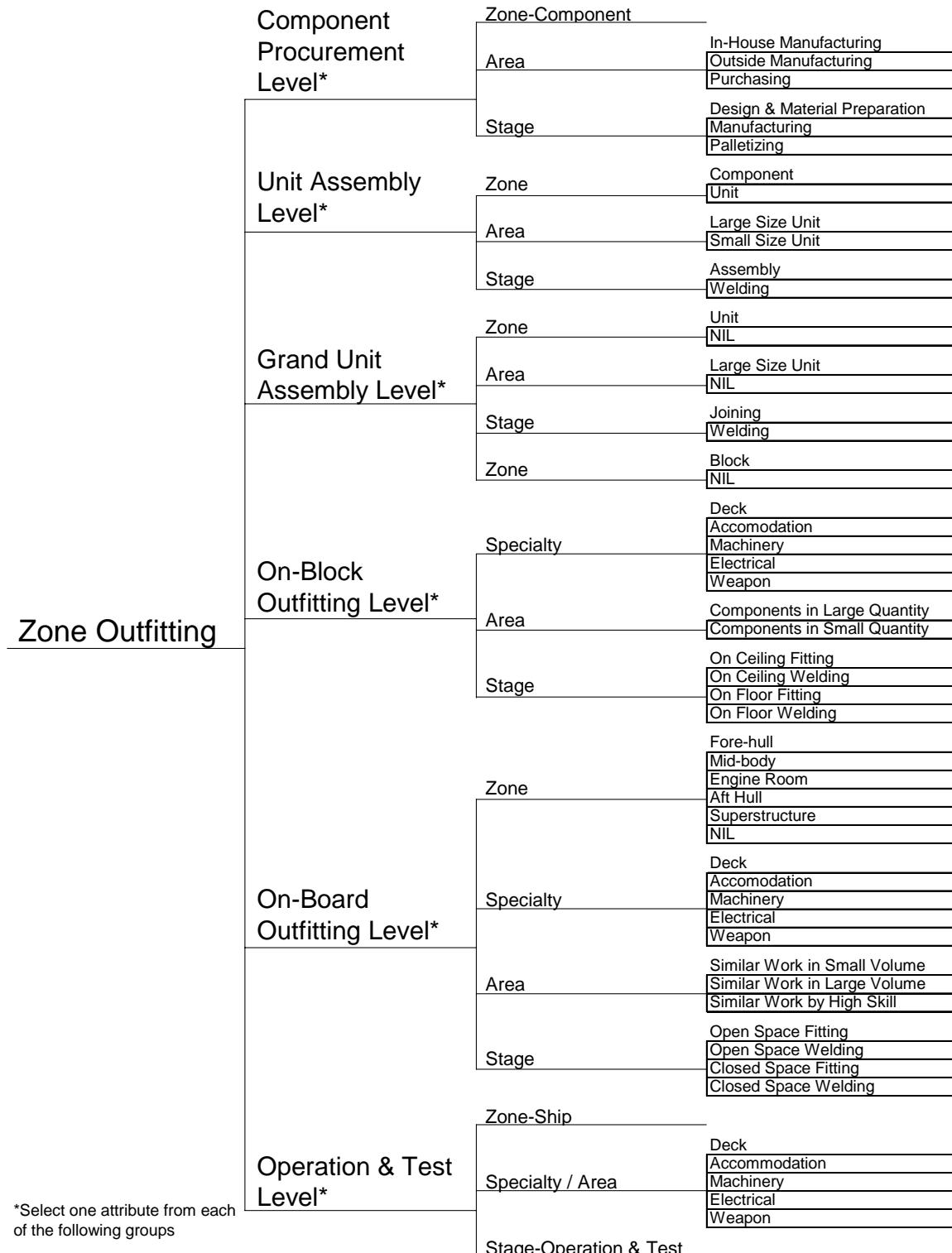


Figure 6. ZOFM Classification Tree (After: <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA452827&Location=U2&doc=GetTRDoc.pdf>)

Zone Painting	Shop Primer Level*	Zone	Material
		Area	NIL
		Stage	Plate Shapes & Other
		Zone	Blasting Painting
		Area/Paint Material	Component Block Onboard/Fore Hull Onboard/Cargo Hold Onboard/Engine Room Onboard/Aft Hull Onboard/Superstructure
		Area/No. of Coats	Conventional Epoxy Inorganic Zinc Other
		Area/Zone Type	One Coat Multiple Coats
		Stage	Burn/Wear Damage Difficult Position Clean Area
		Zone	Surface Prep Cleaning Painting
		Area/Paint Material	Surface Prep After Turning Cleaning After Turning Painting After Turning
		Area/No. of Coats	Component Unit to be Fitted at Onboard Outfitting Component Fitted On-block at On-block Outfitting
		Area/Zone Type	Onboard/Fore Hull Onboard/Cargo Hull Onboard/Engine Room Onboard/Aft Hull Onboard/Superstructure
		Stage	NIL
		Zone	Conventional Epoxy Inorganic Zinc Silicate Other
		Area/No. of Coats	One Coat Multiple Coats
		Area/Zone Type	Burn/Wear Damage Difficult Position Clean Area
		Area/Scaffold	Scaffolding Required Scaffolding Not Required
		Stage	Surface Prep Cleaning Touch Up Painting
		Zone	Surface Prep After Turning Cleaning After Turning Touch Up After Turning Painting After Turning
		Area/Paint Material	Component Unit to be Fitted at Onboard Outfitting Component Fitted On-block at On-block Outfitting
		Area/No. of Coats	Onboard/Fore Hull Onboard/Cargo Hold Onboard/Engine Room Onboard/Aft Hull Onboard/Superstructure
		Area/Zone Type	Conventional Epoxy Inorganic Zinc Silicate Other
		Stage	One Coat Multiple Coats
		Zone	Burn/Wear Damage Difficult Position Clean Area
		Area/Scaffold	Scaffolding Required Scaffolding Not Required
		Stage	Surface Prep Cleaning Touch Up Painting

*Select one attribute from each of the following groups

Figure 7. ZPTM Classification Tree (After: <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA452827&Location=U2&doc=GetTRDoc.pdf>)

G. DETAIL DESIGN AND PLANNING

Detail design, planning, and procurement begin after contract award. The shipbuilder determines detailed construction procedures and methods for ship construction, during this phase of the shipbuilding process. Requirements identified in the bidding and contracting phase provide the basis for determination. Resources are allocated, both material and staffing, and expected completion times are established. The detail design phase uses the ship specifications, contract drawings and GFI or VFI to create detailed drawings needed for construction.

First, development of system level drawings and analyses ensure the design is as intended and will perform to requirements. Production level drawings result from drawing development after design validation. Planning for production begins in the preliminary design process. As noted earlier, the initial design and planning activities use the SWBS orientation and then transition to PWBS. This is apparent when reviewing the four primary design stages:

Basic Design – output is usually contract documents specifying the make up of the ship as a total system and a preliminary build strategy.

Functional Design – output is usually system diagrams and key plans, including list of materials by system.

Transition Design – output is a regrouping of the system's information to provide drawings organized by zones.

Work Instruction Design – output is the more detailed information about the particular interim product used for classification and coding.

Figure 8 depicts the process involved in the development of work packages. The integration of planning, using an iterative approach, strives to ensure these packages are suitable for production. The preliminary or basic design phase produces an initial build plan using the contract documents and provided milestones. The build plan identifies the particular capabilities of the shipyard, along with modifications and/or capital investments required to complete the project. Using the shipyard's experience, the build plan considers block breakdowns, the layout of processing lanes and other best practices to establish production precedence early in the design process (Storch, 1995).

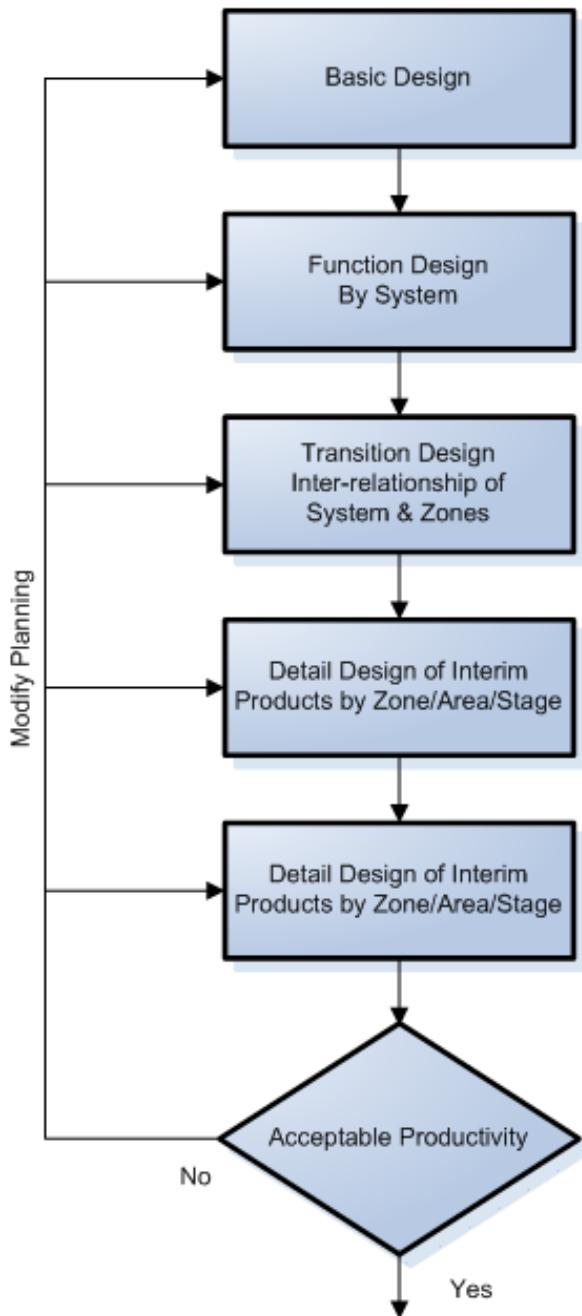


Figure 8. Work Package Development Process (After: Storch, 1995)

Functional Design is the phase of the detail design, where contract design outputs develop into full technical specifications, final hull parameters are developed, major equipment vendors selected, systems requirements refined, and sufficient detailed design

information collected. The finalization of design schedules, budgets and required manufacturing deliverables enables transition to the design development phase.

The notional integrated master plan developed during contract design provides the basis for an integrated ship design and construction plan. Constraints requiring an overlap between ship design and construction drive the requirements for this plan. The integrated plan takes into consideration contract milestones, delivery dates, available facilities, and the type, size and construction methods of the ship to develop a parts fabrication schedule, build sequence and integration schedule. A material schedule is then developed based on the required need date and lead-time for all material including the major vendor supplied equipment.

The transitional design phase of the detail design process shifts from a ship-wide systems engineering approach to a modular, or zone focused approach, based on the build strategy selected for production. The detail design also shifts from an engineering focus to a fabrication based product model focus. The majority of the design and verification takes place in the transition design phase.

The work instruction design phase extracts all engineering data embedded in the Computer Aided Design (CAD) and Product Models as production drawings. Mold loft work usually begins in this phase. It entails the development of Numerical Controls (N/C) data for burning, steel parts programming, and the development of templates (Storch, 1995). The information extracted from the production drawings includes bills of material and any other available numerical control data used to control machines automatically.

Configuration control is critical in this phase. Proper execution of the manufacturing process depends on having the latest data, baseline consistency between related drawings, and the proper accountability of design changes in the manufacturing process.

H. PLANNING, SCHEDULING, AND PRODUCTION CONTROL

The shipbuilding process involves procurement of tons of raw materials and thousands of components. It requires the manufacturing of thousands of parts from raw

material and the assembly of manufactured parts and components into assemblies, blocks, and grand blocks. As such, very complex and detailed planning is required and must be coordinated with engineering in the early stages of the design process.

As stated previously, preliminary planning occurs between the bidding process and contract award. Particular attention to the customer's requirements is necessary. As the process moves into detail design, the decision makers determine what parts, assemblies, and systems are to be built and/or purchased. Determination of the facility layouts, construction methods, subcontracting, sequencing of operations, manufacturing and workforce utilization is also required.

During this stage, production engineers define the size and weight of blocks as allowed by shipyard capabilities. The planning department directs the selection of assembly and erection processes that are consistent with safety regulations and the identification of preliminary zones, problem areas, staging areas and work packages for block assembly and parts manufacturing. The objective of planning is to simplify work as much as possible in an effort to increase productivity by shifting work to the “manufacturing stages where it is safer and easier to perform” (Storch, 1995).

An example is outfitting on-unit as compared to on-block. On-unit is an in-house zone, such as a shop, independent of the hull structure, where the arrangement of fittings are defined and assembled. Outfitting on-block refers to the assembly of fittings on any hull structural subassembly. A ceiling in the on-block zone is set upside-down to facilitate ease of welding. The outfitting process is more productive when conducted in a shop than on-block due to space limitations and potential interference with the multiple crafts involved in the process.

Likewise, outfitting on-block is far more productive than outfitting on-board, which occurs during hull erection and after launch. It is easier to perform different weld techniques on ceilings while an assembly is in the upside-down position as opposed to welding overheard on-board with the unit in the up position (Storch, 1995). “Whether such work is effectively planned and finally incorporated in zone/problem area/stage

work instructions depends on how well designers and production engineers communicate with each other, beginning in basic design and continuing throughout the entire design process" (Storch, 1995).

The planning phase determines all required jobs and job sequencing. As part of the planning process, material, manpower, workstations, cost estimations and job durations are developed within the framework of the master construction schedule. The shipbuilding master schedule provides dates for start fabrication, keel, launch, and delivery for contracted and/or potential ship construction within a reasonable period. The outcome is a design department master, which controls the sequence of other design schedules.

The Planning and Scheduling department is responsible for the detailed build strategy along with the master plan, which establishes need dates for major equipment and procurement plans. Planners then refine the master plan to lower level production schedules, which allow for proper planning and managing of shipyard resources such as facility layout plans, shop loading, manning plans and sub-contractor activities.

Scheduling methods generally reflect best practices developed from lessons learned. A network flow diagram provides an overall schedule of task and events to both management and production, which illustrates the sequence of work and the task relationships to the shipbuilding project (The Society of Naval Architects and Marine Engineers [SNAME], 1980).

The basic principle in network flow is the task-to-task with a task- to-time relationship. An example is that task C cannot start until its prerequisite tasks are complete. Some examples of the Network Flow Scheduling Technique are the Program Evaluation and Review Technology (PERT) and the Critical Path Method (CPM). Both examples provide a means of representing graphically the different tasks that are required for a project. Revised networks show the impact of adjustments to a schedule resulting from design changes and schedule delays. It is also possible to determine the shortest and longest probable time for project completion. Figure 8 shows a Critical Path Method network for a small portion of an overall ship schedule.

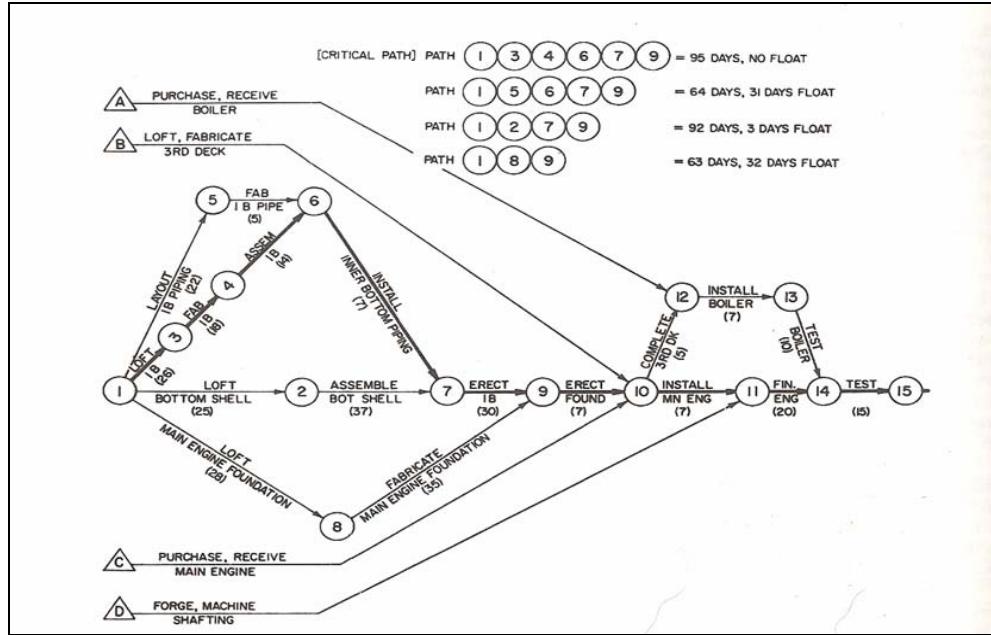


Figure 9. Scheduling Network for Critical Path Method (From: Storch, 1995)

It is important to keep networks simple as well as practical and to eliminate insignificant tasks; otherwise, the network will become unmanageable and not add value to the shipbuilding project. Revising schedules requires a new critical path to be developed. It is also important to mention that in the shipbuilding process, there will be more than one critical path and that each department will have its own critical tasks relative to the production process.

I. CONSTRUCTION

Start fabrication marks a major milestone in the shipbuilding process. It begins with production of steel parts and hull block manufacturing. This is a critical step in the production process as it is the foundation for all outfitting work. Any delays or failures influence downstream outfitting and assembly processes. Once production begins, it becomes extremely difficult to make modifications to existing technology, add new technology to the ship, and/or make schedule adjustments. Design changes or schedule delays because of poor planning and coordination of required resources may drive new requirements (Kanerva, Lietepohja, & Hakulinen, 2002). The Design Engineering phase

runs in concurrence with the production process. As such, the outputs of the design process must sufficiently identify material and production requirements to allow for procurement, planning, and scheduling to enable efficient manufacturing and installation of ship components (Kanerva, 2002).

Pre-outfitting begins during the block and grand block assembly stages. This entails installation of piping, ladders, ventilation, insulation, cable, etc. Decisions on the extent of pre-outfitting is largely dependent on the time available for pre-planning, development work and equipment procurement. Increased pre-outfitting increases scheduling, design and construction problems such as component availability and protection against damage during and after hull erection. There must also be a high degree of accuracy in system layout and a carefully planned installation sequence to avoid lockouts and interferences, which would require rework or a design change to correct the problem (SNAME, 1980). Lockouts refer to the removal of temporary accesses, used for equipment installation, prior to installing equipment larger than any remaining access. This results in cutting another temporary access in a completed compartment.

Typical shipyard construction tasks are not sequential and may occur at different times in the construction process (Kanerva, 2002):

Steel preparation – is the process of cleaning and preparing steel parts or blocks for painting or corrosion control. Use of various techniques depends on the type of material prepared.

Steel parts manufacturing – is the process of cutting and fabricating steel plates into panels and bent shells required for hull block assemblies.

Outfitting component prefabrication – involves manufacture of piece parts and components required for outfitting. This includes items such as pipe, duct, electrical components, etc.

Unit prefabrication – builds and outfits assemblies such as machinery spaces, which usually go through a series of tests prior to landing on-block.

Block assembly – takes parts produced from the Steel manufacturing stage assembled into blocks.

Block outfitting – takes parts produced in the outfitting component stage and/or purchased components for installation into block assemblies.

Grand Block assembly – joins pre-outfitting block assemblies to form larger blocks prior to hull erection.

Grand Block outfitting – takes parts produced in the outfitting component stage and/or purchased components and continues outfitting on the grand block prior to hull erection.

Hull Erection – begins with lay keel and is the process of landing and joining grand block assemblies at the construction-building site.

Area Outfitting – once hull erection begins, the outfitting of parts produced in the outfitting component stage and/or purchased components continues using a zone area process.

Test and Trials – demonstrates, through a series of tests, that all systems and equipment are properly installed and operable in accordance with contract requirements.

The Production Control (PC) department is responsible for preparation of work packages and ordering of material required to complete the job and maintain even workloads throughout the various workstations within the construction process. They coordinate with other organizations to support production schedules on bill, test, and compartment completions, material status and labor loading of shops, control of docks and areas, major event status, critical path analyses, workarounds and work station transfers. PC identifies problems and acts as a liaison with other departments to provide resolutions. Due to working many aspects of ship construction concurrently, it is important to monitor the progress in order to know what is actually happening in the production process. PC typically performs this function.

Material control is one of the most important functions in applying and controlling group technology in shipbuilding. Purchasing material and component parts necessary to ensure the flow of needed material to various workstations without overstocking requires careful scheduling and planning. Material Control is responsible for purchasing, requisitioning, expediting, warehouse, and delivery of material to the workstations. Figure 10 illustrates the relationships of material between design, procurement, and production.

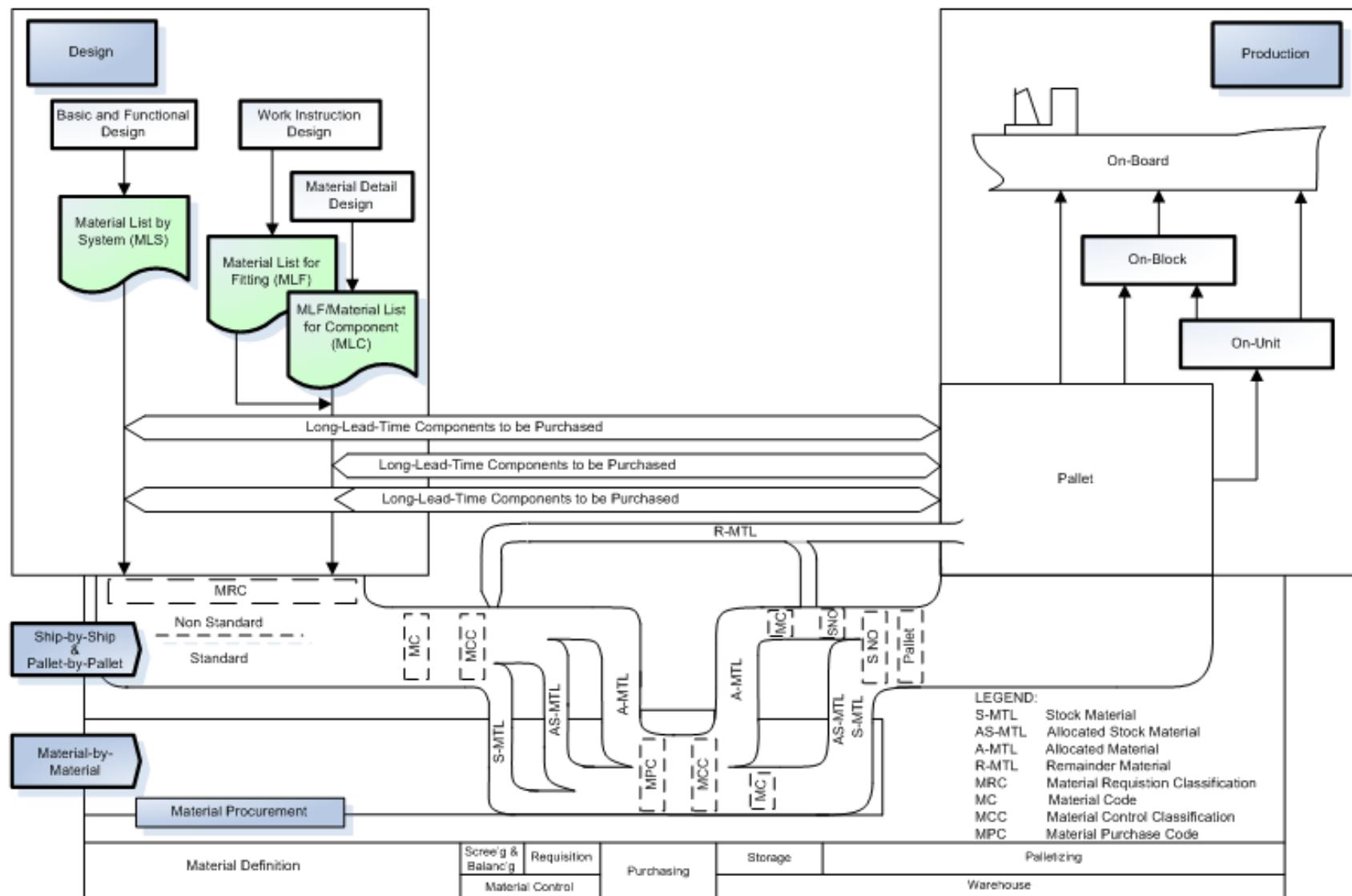


Figure 10. Material relationship – Design/Procurement/Production (After: Storch, 1995)

Material lists identify equipment by system as well as zone, problem area and stage of production. Material control numbers identify type, grade and size required for procurement. Material cost classification numbers identify a system to allocate cost, a piece number which identifies by system where they appear in the design and a work package number to designate where it will be installed by zone/problem area/stage (Storch, 1995).

As stated earlier, material control manages the warehousing function. It receives and stores material until receiving an order for palletizing and delivery to the workstation. The release and on-time delivery of material requires an advanced request, with sufficient time to allow for palletizing. Figure 11 illustrates this process flow (Storch, 1995). The goal of warehousing is to maintain an accurate count and physical control of material while minimizing handling and storage costs.

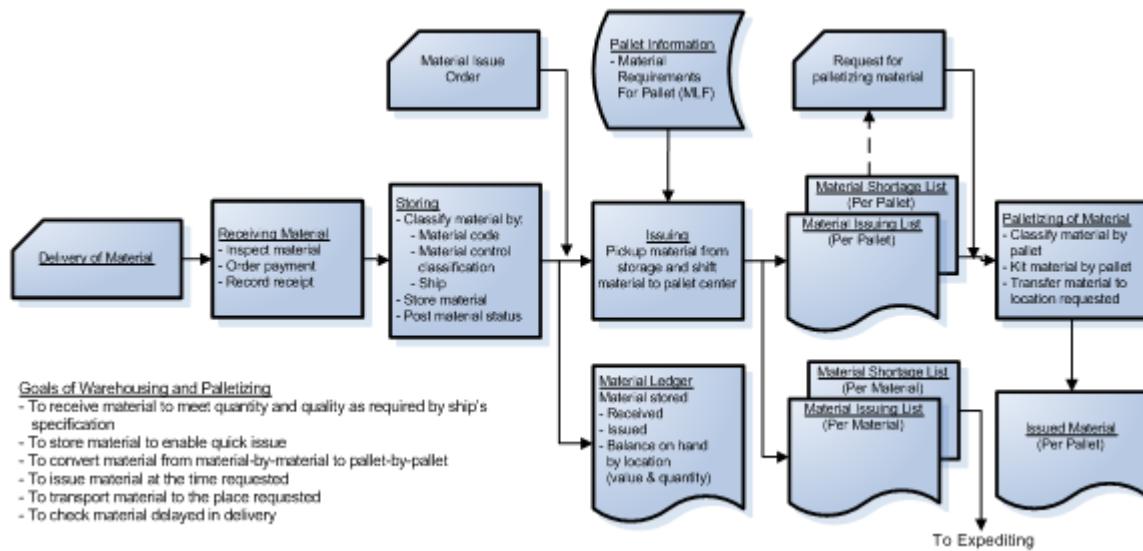


Figure 11. Functional flow of warehouse and palletizing (After: Storch, 1995)

Accuracy Control monitors the construction of in-process work to minimize delays and rework. It involves the regulation of accuracy as a method for improving shipbuilding productivity by focusing on areas where significant benefits result from improvements in the process. Accuracy Control also provides visibility by individual work processes or problem areas and creates a quantitative feedback loop between production, planning, design, and engineering.

Accuracy Control involves the regulation of accuracy as a management technique for continuous improvement of the entire manufacturing system. To obtain productivity improvement, shipbuilders identify and prioritize problems. The statistical basis makes clear the relationship between cause and effect (DOT, 1985).

Test and evaluation (T&E) starts in the early construction phase, with a detailed test schedule and commences with the successful demonstration of the ship's systems during final contract trials. It consists of seven discrete stages of testing, with each stage building on the results of the previous one. Stage 1 tests are normally considered a function of the quality assurance department as opposed to T&E. DoD-STD-2106 (Navy) defines the seven stages of industrial testing as follows:

Stage 1 – Material Receipt Inspection and Shop Tests. Normally considered a function of quality assurance as opposed to T&E, stage 1 tests intend to ensure receipt of equipment in good shape. They also facilitate inspection of new or repaired equipment prior to installation onboard ship.

Stage 2 – Shipboard Installation Inspections and Tests. Stage 2 tests and inspections intend to ensure the proper installation of equipment prior to operation.

Stage 3 – Equipment Tests. Stage 3 tests demonstrate the individual equipment performs within the established limits and tolerances.

Stage 4 – Intra-system Tests. Stage 4 tests demonstrate that equipment and required functions, entirely within one independent system, perform within established limits and tolerances.

Stage 5 – Inter-system Tests. Stage 5 tests demonstrate that two or more independent systems perform a specific function or functions within established standards.

Stage 6 – Special Tests. Stage 6 tests, conducted as part of the dockside work package, require special simulation resources external to the immediate test organization.

Stage 7 – Trial Tests. Stage 7 tests must be conducted during sea trials.

Test procedures define the information required for validation and verification of the customer's requirements, regulatory bodies' regulations, and shipbuilder recommendations. They may be government or contractor furnished, generally depending on who provides the equipment. Usually systems that are vendor furnished require test procedures provided by the shipyard or a subcontractor.

Test conductors conduct tests in accordance with the test procedures and memorandum as systems are completed. The following provides a high-level overview of shipboard testing:

Dockside Trials – tests conducted in order to ensure proper installation and hook up of systems in preparation for sea trials. Typical dockside testing consists of stage 2 – installation and inspection tests; stage 3 – initial equipment light off; stage 4 – intra-system tests; stage 5 – inter-system tests; and stage 6 – special tests.

Builder's Trials – at-sea tests conducted by the shipbuilder in order to locate and solve potential problems prior to Acceptance Trials.

Acceptance Trials - official sea trial conducted with the customer, underway.

Final Contract Trials – tests conducted after delivery of the ship in order to resolve open trial cards and discrepancies.

Stage 3 unit or stand-alone tests may support the PWBS classification and coding.

However, most test and evaluation activities require the transition back to the SWBS structure. The Management Cycle shown in Figure 2 illustrates the transition from zone orientation back to systems for the final evaluation period.

J. CHAPTER SUMMARY

In the course of investigating the overall shipbuilding process, significant overlap of design, planning, material procurement and production, as well as, functional systems and product aspects have been observed. Information exchange varies as the building of the ship advances but communication between the shipyard and all stakeholders is an ongoing process. Overlap in the design, planning, scheduling and construction processes are essential for reducing the construction period. However, it also reduces the time allowed to organize information developed by designers. Design information must be formatted to anticipate needs related to material and production requirements from the beginning stages.

Lead-time required for design development and manufacturing of components increases with the level of sophistication, complicating the planning efforts. It is common practice to sub-contract small aspects of the ship to other shipyards or organizations to meet production schedules and need dates. Subcontractors may not be familiar with

current processes or construction details that occur during design synthesis. Without proper management, their effort could negatively affect concurrent shipyard activities. This adds complexity to the process, and reinforces the importance of early and accurate planning.

IV. DESIGN CHANGE

A. INTRODUCTION

There are many reasons for design changes throughout the design and construction of a ship. These changes result in additional work effort, even if not implemented. Changes often lead to rework. The timing of these changes can have a direct and cascading impact requiring additional labor hours, and increased material costs. With this in mind, it seems design change would be discouraged. Unfortunately, the time it takes to build a ship, and the rapid refreshing of technology, not only encourage design change, but also make it a necessity.

The goal is to provide the Warfighter battle space dominance while keeping overall cost low enough to allow a consistent purchase of additional ships. Since some design changes are necessary, how can the impacts be minimized? It is important to understand what causes design changes and how the changes affect the ship design and construction process at different stages. Knowing the cause and magnitude of the impacts should provide a basis for determining which changes are necessary, and which do not provide a benefit outweighing the cost.

Common sense dictates that it is less costly to change the placement of a window during design, prior to construction. It is much more expensive to remove a window from its initial location, after installation, and then relocate it. The timing of the design change has significant relevance to the impact on cost and schedule. A cost analysis should consider this. The benefit of moving the window from location A to location B may warrant the cost of change during the design phase. However, the dramatic cost increase associated with making the change after installation of the window in location A, may make the move infeasible.

What constitutes design change? The more evident occurrence is changing from a previously specified item or system to a different item or system through some type of contract modification. Depending on the timing of the change, this results in rework of

specifications, drawings, planning, scheduling, and possibly construction and test. At a minimum, the change itself consumes resources associated with scoping and submitting a proposal.

Lack of information is also a form of design change. Information missing during detail design results in reservations on a drawing required by a specific date to accommodate ship construction. Once provided, the designer uses the information to generate change documentation or a new revision of the drawing. This leads to updates in planning, scheduling, and possibly construction and test.

In a 2005 survey conducted for the UK Ministry of Defense, RAND asked shipbuilders to identify key factors that led to program slippage. The survey included shipbuilders from the United Kingdom, United States and European Union identified in Table 1. RAND presented the six categories shown in Figure 12 and asked the shipbuilders to appropriate the percentage each contributed to schedule slippage for a total of 100%. The shipbuilders identified change orders/late product definition as the main contributors at 46%. Somewhat related to late product definition, lack of technical information, accounted for an additional 23% (Arena, Birkler, Schank, Riposo, & Grammich, 2005).

UK Shipbuilders	US Shipbuilders	EU Shipbuilders
BAE Systems	Bath Iron Works	Chantiers de l'Atlantique (France)
Babcock BES-Rosyth	Electric Boat	Fincantieri (Italy)
Devonport Management Ltd.	Kvaerner Philadelphia	IZAR (Spain)
Ferguson	National Steel and Shipbuilding Company	Kvaerner Masa (Finland)
Swan Hunter	Northrop Grumman Ship Systems	Royal Schelde (The Netherlands)
Vosper Thورncroft		

Table 1. UK, US, EU Shipbuilders Surveyed (After:
http://www.rand.org/pubs/monographs/2005/RAND_MG235.pdf)

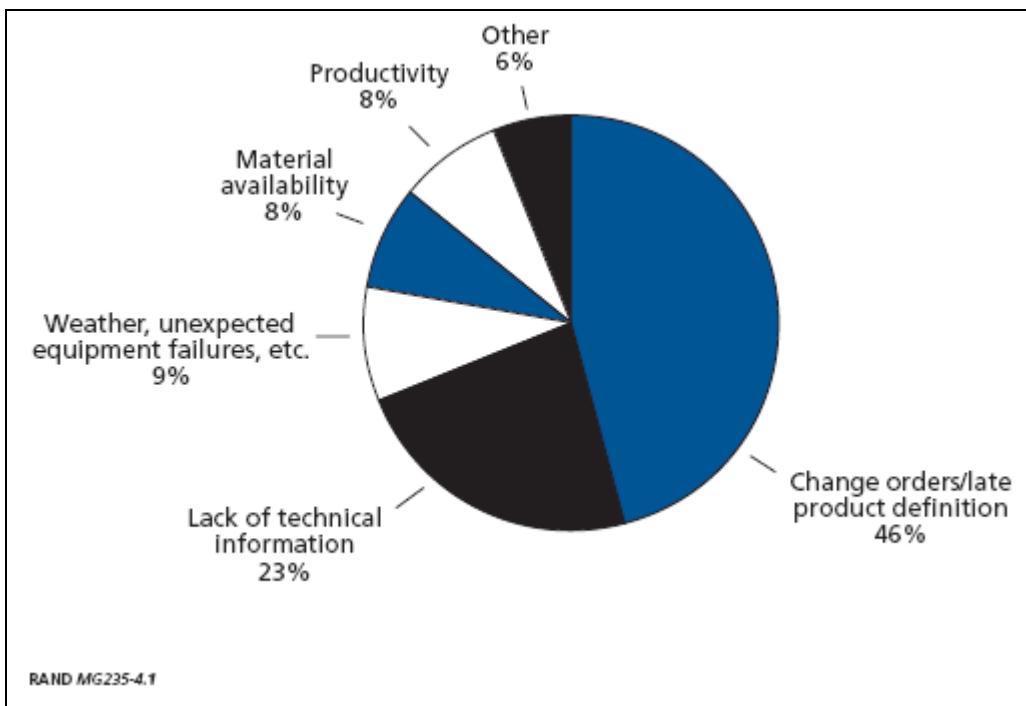


Figure 12. Causes of Schedule Slips Reported by Shipbuilders (From: http://www.rand.org/pubs/monographs/2005/RAND_MG235.pdf)

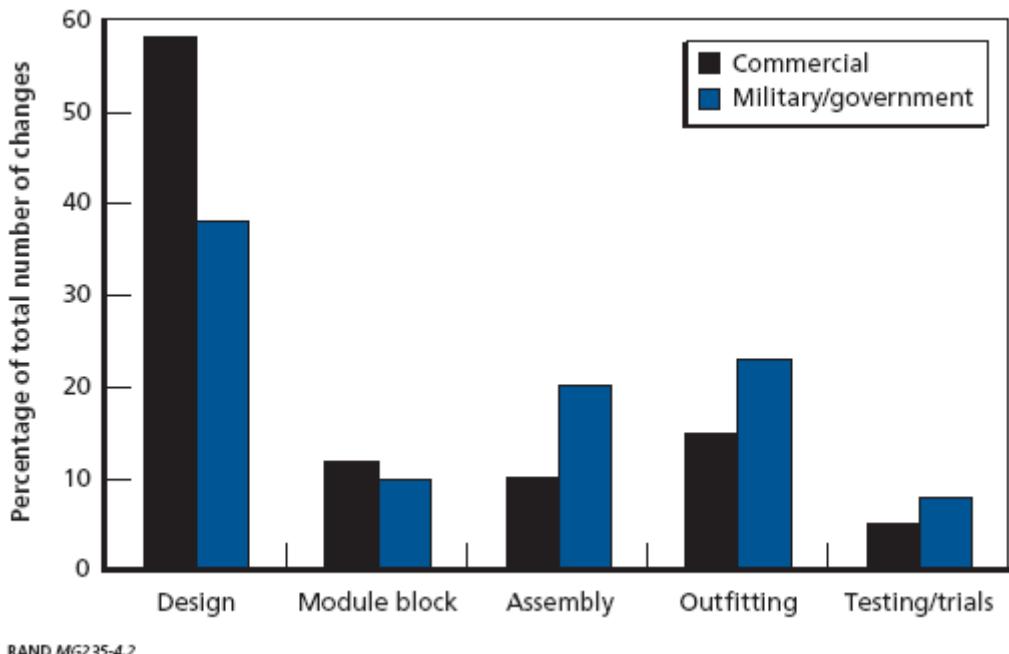
The timing of the design change has a direct impact on cost and schedule. RAND's comparison of commercial change orders to military contract change orders by phases is shown in Figure 13. The analogy supports the view that changes occurring later in the program are more disruptive and have a much greater impact:

Average value of total contract cost for changes associated with commercial contracts is 4%, and 8% for military.

On average, changes incurred on commercial contracts usually take one to five weeks to resolve as compared with four to 22 weeks on military contracts.

Roughly, 60% of changes on military contracts occur much later in the production phase of the contract, whereas, more than half of design changes on commercial contracts occur in the early design phase.

The cost of change as it occurs in the design phase is generally limited to the loss of design time because of the change. However, once production begins, the cost of change is more expensive because it leads to rework of previously completed ship construction tasks (Arena, 2005).



RAND MG235-4.2

Figure 13. Percentage of Total Number of Changes Occurring at Various Production Phases (From: http://www.rand.org/pubs/monographs/2005/RAND_MG235.pdf)

The GAO analyzed the substantial cost growth on eight ships in the four classes comprising 96 % of the new ship construction budget in 2005. Their analysis attributes increases in labor hours and material costs for 78 % of the cost growth of these ships (United States Government Accountability Office [GAO], 2005a). Table 2 from the GAO report lists the reasons cited, by the respective shipyards, for cost growth in labor hours (GAO, 2005a). Design changes are a common theme across all ship classes.

Case study ship	Reasons for increase
DDG 91	<ul style="list-style-type: none"> • Inexperienced laborers • Design upgrades that result in rework
DDG 92	<ul style="list-style-type: none"> • Introduction of a new construction facility, setting workers back on the learning curve • Design upgrades that result in rework and workarounds • Strike increased number of hours needed to construct ship
CVN 76	<ul style="list-style-type: none"> • Less-skilled workers due to demands for labor on other programs at shipyard • Extensive use of overtime • Design changes resulting in rework
CVN 77	<ul style="list-style-type: none"> • Late material delivery results in delays and workarounds • Design changes resulting in rework
LPD 17	<ul style="list-style-type: none"> • Inexperienced subcontracted labor • Design difficulties led to doing work out of sequence and rework • Schedule delays • Bused workers to meet labor shortages
LPD 18	<ul style="list-style-type: none"> • Increases in LPD 17 translated into more hours for LPD 18
SSN 774	<ul style="list-style-type: none"> • Late material delivery • First in class design issues
SSN 775	<ul style="list-style-type: none"> • Quality problems and design changes • Inclusion of non-recurring labor hours

Sources: Shipbuilder (data); GAO (analysis).

Table 2. Reasons Given by Shipbuilders for Labor Hours Cost Growth (After: <http://www.gao.gov/cgi-bin/getrpt?GAO-05-183>)

Current events provide several examples of the high number of design changes in today's shipbuilding projects. In a testimony before the House Armed Services Committee, Philip Teel, Sector President of Northrop Grumman Ship Systems, stated that 5,750 design changes occurred between LHD 1 and LHD 2, with an average of 3,550 for each follow-on LHD (Teel, 2007). Teel provided notable metrics, which support the observation that cost growth in military ships is greater than that of commercial

shipbuilding projects, due to design modifications. Figure 14 illustrates the high number of design changes in both first of class military ships, and follow-on ships as compared to that of commercial ships (Teel, 2007).

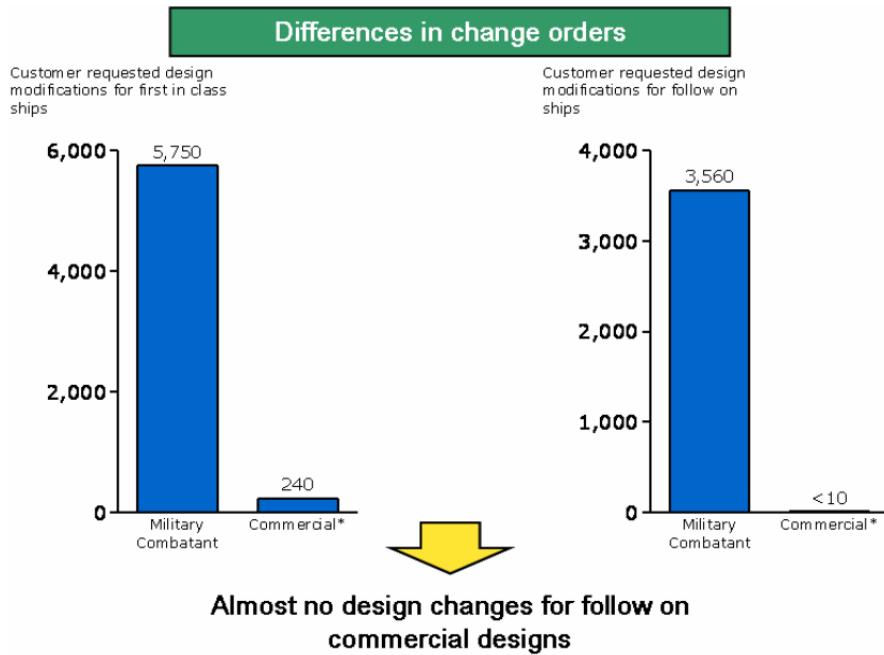


Figure 14. Comparison of Military and Commercial Change Orders (From: http://armedservices.house.gov/pdfs/SPEF032007/Teel_Testimony032007.pdf)

Storch, Hammon, Bunch, and Moore (1995) provide an excellent overview of the theoretical, economical model of shipbuilding, while explaining the importance of maintaining an optimum production rate. Work packages are developed and scheduled to support construction of interim products. These interim products are then available for assembly in the next higher interim products and so on. The production rate varies over time depending on the resources required for the currently scheduled interim products.

Planning and scheduling considers all of these dependencies when developing the work packages and schedules. Some slack time exists, but changes usually represent additional work, performed out of the normal sequence, and therefore affecting the schedule of other work packages (Storch, 1995). It is important to understand that design changes are major cost drivers due to the instability they introduce in maintaining an optimum production rate (Storch, 1995).

While some changes are necessary, many design changes are the result of avoidable issues. Inadequate requirements generation allows ambiguity to affect all follow on activities. This usually shows up during detail design and requires additional engineering and possibly programmatic effort to unravel the missing or incorrect information. Once the ship construction contract is signed, any changes in contract documentation or government/vendor furnished information is considered out of scope work and usually requires some type of cost adjustment.

The acquisition process includes many reviews that attempt to minimize these types of risks. However, it is extraordinarily challenging to be accurate given the complexity of ship design and the politics surrounding the budget. This is evident when reviewing the vast number of change orders levied on the shipbuilder within a few months after signing a contract. LCS 1 faced an additional 14,000 new requirements, introduced by the Naval Vessel Rules, after contract award (Moosally, Moak, McCreary, Ellis, 2007). “This in turn drove many of the over 600 engineering changes on the lead ship” (Moosally, 2007). Figure 15 shows the disruption introduced by the design changes to LCS 1.

First Of Class Design & Construction Execution

Littoral Combat Ship

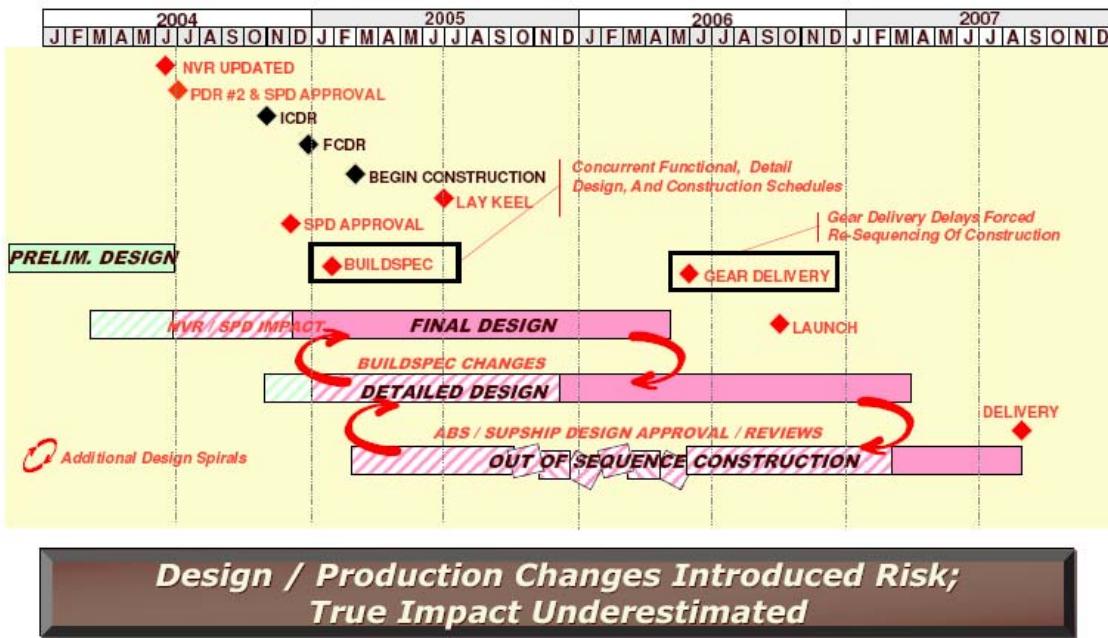


Figure 15. LCS 1 Master Schedule Including Design Change Impacts (From: http://armedservices.house.gov/pdfs/SPEF_LCS020807/Industry_Testimony020807.pdf)

In some cases, the customer believes changes will reduce cost. Their estimate includes only the reduction in material and labor costs to accomplish the initial scope of work. They fail to recognize the cost of the effort already expended to perform preliminary detail design, scheduling, planning, purchasing, and many other related tasks. The shipbuilder must recoup these costs, along with the cost to develop a bid package and negotiate the estimate to incorporate the change.

If the customer has not put a “stop work” in place, work continues according to the initial contract. That means the cost of the change continues to grow during the time it takes to scope, negotiate, and authorize the change. These factors make estimating design changes complex, with risk that many impacts may be completely missed. They also show the need for understanding the desired change and its effect on ship design and construction, as well as the importance of communication between the customer and industry.

Often what seems like a small modification ends up cascading through several seemingly unrelated areas. An investigation of the sources of design changes, as well as their effects on cost, will provide insight into what design changes should be discouraged and what can better mitigate the effect by those that are necessary.

B. SOURCES

1. Requirements

Until recently, ship performance and design requirements were decomposed from the Operational Requirements Document (ORD). The ORD described the high level, mission based requirements. The ultimate solution to the ORD requirements is the design, or contract data package, which contains the ship specification. For the shipbuilder, the ship specifications are **the requirements**. They are the specifications for building the ship.

There is an obvious, compelling need for the ship specification to be clear, concise, and unambiguous. However, in the compressed environment of the specification development, their concurrent development may lead to inconsistencies that need correction. Over the development period, new technologies may require updates. The needs of National Defense may change, requiring updates to ship mission requirements, and therefore the ship specification.

There are numerous causes of requirements change. These changes may originate with either the Navy or the shipbuilder. The shipbuilder generally proposes changes to clarify, disambiguate, correct errors, or improve producibility. The Navy typically proposes changes for the same reasons, as well as for mission, technology, affordability (remove capability), and political. The concern with requirements change is the effect on design; they are essentially a design change. Changes to requirements pose the risk of great impact on cost and schedule due to their direct influence on the design. The impact is not one of additional cost above the baseline; rather it is to the baseline not yet defined by the detail design and construction contract.

Requirements change may occur any time after Milestone A. Prior to Critical Design Review (CDR), activities analyzing and decomposing the ORD, or equivalent, contribute to the ship specification development. As the analysis matures, the stability of requirements makes possible the ship specification. This is a time of controlled volatility, with increasing configuration management until reaching CDR. Changes in this period indirectly affect rework when they create ambiguity and errors in the ship specification, or address the modifications improperly. While these changes may have dramatic cost and schedule ramifications, they do not generally require rework. The issue rather, is the total volatility of the specifications as the program prepares to strike a baseline at CDR.

After CDR, with the exception of administrative changes, the issue is with the direct influence of changes on the design. As the detail design matures, changes initially create engineering and producibility/planning rework. After construction starts, the potential for engineering and construction rework magnifies the effect, including out of sequence complications. Therefore, there are two periods in which requirements change affects rework. Pre CDR, the effect is by total volatility. Post-CDR, the effect is based on the unique change.

2. Technology Maturity

The introduction of immature technologies into ship design and construction increases the risk for design change and out of sequence work. This continues to be common practice in DoD acquisitions. In the 1999 report, Better Management of Technology Development Can Improve Weapon System Outcomes, the GAO assessed best practices on how to improve incorporation of new technology into weapon system programs. The report reviews experiences of both DoD and commercial technology development cases.

Review of practices indicates that programs incorporating technologies with a high level of maturity are more likely to succeed. Programs that do not identify or resolve gaps in technology maturity, prior to product development, result in higher cost and schedule slippages (GAO, 1999). In order to avoid cost growth and delays, commercial firms make an important distinction between technology development and product

development (GAO, 1999). They practice managing a technology's maturity to ensure it supports the intended product's requirements prior to using it in product development (GAO, 1999).

In its review, the GAO discovered that the commercial industry followed a disciplined process in achieving technology maturity. This is not the case for the DoD. Due primarily to budget constraints and pressures to provide unique performance capabilities at a low cost, the DoD is more likely to move immature and unproven technology into product development (GAO, 1999). Table 3 depicts a correlation of cost and schedule growth to lower Technology Readiness Levels (TRLs) (GAO, 1999).

Product development			
Product Development and associated technologies	TRL at program launch	Cost growth	Schedule slippage
Commanche helicopter		101 percent*	120 percent*
Engine	5		
Rotor	5		
Forward looking infrared	3		
Helmet mounted display	3		
Integrated avionics	3		
BAT		88 percent	62 percent
Accoustic sensor	2		
Infrared seeker	3		
Warhead	3		
Inertial measurement unit	3		
Data processors	3		
Hughes HS-702 satellite		None	None
Solar cell array	6		
Ford Jaguar		None	None
Adaptive cruise control	8		
Voice activated controls	8		

*The Commanche, in particular, has experienced a great deal of cost growth and schedule slippage for many reasons, of which technology immaturity is only one. Other factors, such as changing the scope, funding, and pace of the program for affordability reasons, have also contributed.

Table 3. Cost and Schedule Experiences on Product Development (After: <http://www.gao.gov/archive/1999/ns99162.pdf>)

TRLs provide an assessment of the maturity level of evolving technologies. As outlined in Table 4 from the Defense Acquisition Guidebook, TRLs range from two to nine, with the increase reflecting an increase in technology maturity. In the course of its study, the GAO found that technology insertion at program launch with a TRL of six to eight usually met cost, schedule and performance criteria. The study further revealed that technology used in commercial programs, prior to product launch, always fell into this category. Technology in DoD acquisitions prior to program launch rarely achieved a TRL greater than five. Using unproven technology in product development, the DoD programs frequently experienced significant cost and schedule overruns (GAO, 1999).

Technology Readiness Level (TRL)	Description
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.

Technology Readiness Level (TRL)	Description
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Table 4. Technology Readiness Level (After:
<https://akss.dau.mil/dag/DoD5000.asp?view=document>)

Unfortunately, an unchecked desire for the latest and greatest technology may put the program at risk. If the contract specifies a new technology but the technology does not mature prior to design, then design change is likely. As time elapses, the potential impact grows. The technology may mature, providing the information and products to incorporate in the ship's design and construction. Alternatively, it may not, resulting in the fall back to a legacy solution. In either case, drawings, planning, schedules, and possibly construction and test are impacted.

Figures 16 and 17 show the processes for incorporating advanced technology into product development by the commercial industry and the DoD, respectively. They each use knowledge points to identify the level of maturity for use in product development. The timing and sequencing of these knowledge points highlights different views.

Commercial industries credit successful launch and delivery of products to the level of knowledge and maturity associated with each phase in the cycle. The firms seek a mature technology prior to product launch. It shows a very clear distinction between Technology Development and Product Development, and the level of knowledge gained prior to production. Their model produces consistent reductions in production development risks, reduced cycle times, reduced cost and an overall smoother production process.

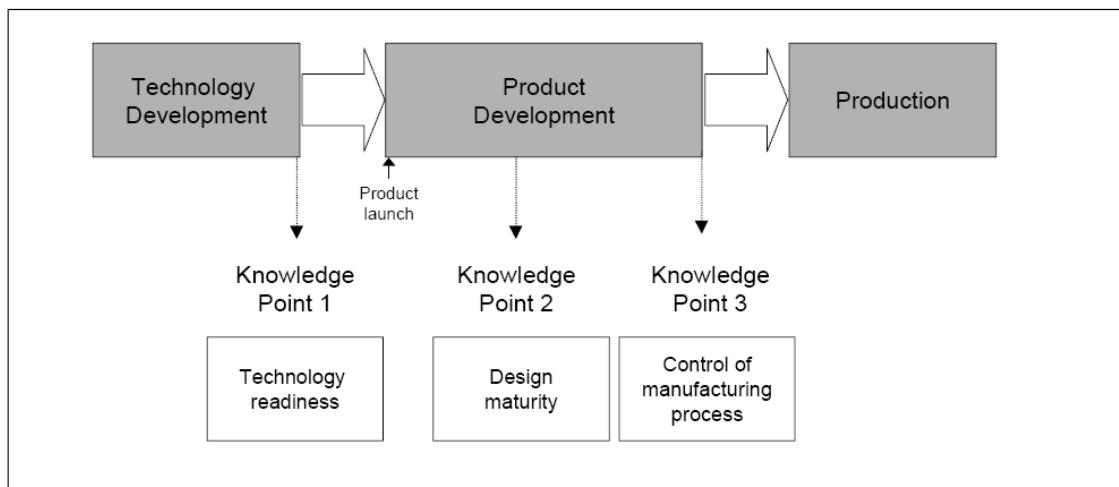


Figure 16. Cycle for Providing Users a Product with Better capabilities (From: <http://www.gao.gov/archive/1999/ns99162.pdf>)

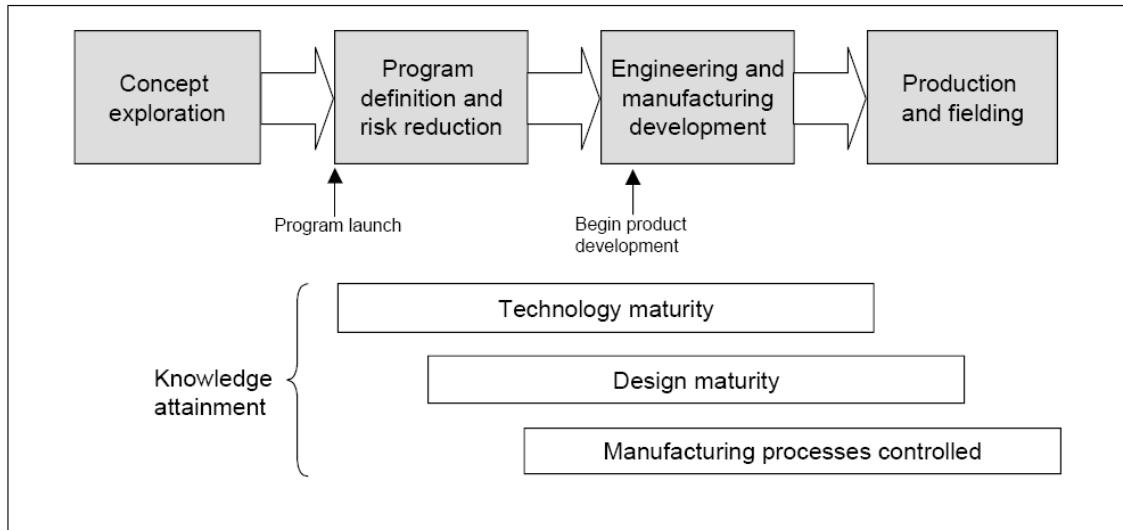


Figure 17. DoD's Weapon System Acquisition Cycle (From: <http://www.gao.gov/archive/1999/ns99162.pdf>)

Figure 17 illustrates the DoD's cycle for development of weapon systems. Unlike commercial firms, the level of knowledge for technology maturity, design maturity, and manufacturing process control, is still developing even as the weapon enters the production and fielding phase. The concurrency of these activities increases program risk, cost, and schedule. DoD does not make the clear distinction between technology development and product development made by commercial firms. Product development starts prior to technology maturity.

The GAO's comparison of the Commercial Industry to DoD led to the determination that "Maturity of Technology at Program Start is an Important Determinant of Success" (GAO, 1999). The report recommended, with concurrence from the DoD, that key technologies achieve a TRL of seven at established points in the process prior to commitment of cost, schedule and performance baselines. However, a 2005 GAO study indicates that the practice of incorporating immature technologies into weapon systems continues today:

Poor execution of the revised acquisition policy is a major cause of DoD's continued problems. DoD frequently bypasses key steps of the knowledge-based process outlined in the policy, falls short of attaining key knowledge, and continues to pursue revolutionary—rather than

evolutionary or incremental—advances in capability. Nearly 80 percent of the programs GAO reviewed did not fully follow the knowledge-based process to develop a sound business case before committing to system development. Most of the programs we reviewed started system development with immature technologies, and half of the programs that have held design reviews did so before achieving a high level of design maturity. These practices increase the likelihood that problems will be discovered late in development when they are more costly to address. Furthermore, DoD's continued pursuit of revolutionary leaps in capability also runs counter to the policy's guidance. (GAO, 2005b)

The report did not address ship programs, but it clearly shows that DoD continues to allow system development with immature technologies. Table 5 contains the data for 23 programs initiated under the revised DoD Acquisition Policy. It clearly shows that several programs did not satisfy the requirements of the various acquisition milestones and checkpoints meant to control risk. For example, the Global Hawk Unmanned Aerial Vehicle did not have a Formal Milestone A review, 0% of the technology rated at least TRL 6, and only 33% of the design drawings were complete at design review (GAO, 2005b).

Program	Program start	Formal Milestone I* or Milestone A decision review?	Percent technology mature (TRL 6) at program start	Percent design drawings complete at design review	Percent growth in estimated development cost ^c	Percent growth in estimated development schedule
Expeditionary Fighting Vehicle	12/2000	Yes	80%	81%	61%	70%
Active Electronically Scanned Array radar (upgrade for F/A-18 E/F fighter/attack aircraft)	12/2000	No	0%	59%	14%	1%
Global Hawk unmanned aerial vehicle	2/2001	No	0%	33%	166%	Undetermined
UH-60M helicopter upgrade	4/2001	No	Not available	Not available	151%	25%

Program	Program start	Formal Milestone I* or Milestone A	Percent technology mature (TRL 6) at program start	Percent design drawings complete at design review	Percent growth in estimated development cost ^c	Percent growth in estimated development schedule
C-130 Avionics Modernization Program	8/2001	No	100%	Not available	122%	Undetermined
Joint Strike Fighter	10/2001	Yes	25%	52% ^b	30%	23%
C-5 Reliability Enhancement and Re-engining Program	11/2001	Yes	100%	98%	0%	25%
Joint Tactical Radio System Cluster 1	6/2002	No	0%	28%	31%	44%
Joint Tactical Radio System Waveform	6/2002	No	Not available	Not available	44%	Undetermined
Advanced Anti-radiation Guided Missile	4/2003	No	Not available	Not available	7%	0%
Multi-Platform Radar Technology Insertion Program	4/2003	No	100%	100% ^b	0%	Undetermined
Future Combat System	5/2003	No	19%	Not available	48%	53%
E-2 Advanced Hawkeye	6/2003	No	50%	90%	5%	0%
Warfighter Information Network-Tactical	7/2003	No	25%	Not available	0%	0%
Small Diameter Bomb	10/2003	Yes	100%	Not available	0%	0%
EA-18G	11/2003	No	60%	97%	7%	0%
Joint Tactical Radio System Cluster 5	4/2004	No	50%	Not available	0%	2%

Program	Program start	Formal Milestone I* or Milestone A	Percent technology mature (TRL 6) at program start	Percent design drawings complete at design review	Percent growth in estimated development cost ^c	Percent growth in estimated development schedule
Multi-Mission Maritime Aircraft	5/2004	No	0%	Not available	0%	0%
Standard Missile-6						
Extended Range Active Missile Block 1	6/2004	No	Not available	Not available	0%	0%
Aerial Common Sensor	7/2004	Yes	50%	39% ^b	45%	36%
B-2 Radar Modernization Program	7/2004	No	100%	84%	0%	0%
Patriot/Medium Extended Air Defense System Combined Aggregate Program (fire unit)	8/2004	No	83%	Not available	0%	0%
Mission Planning System	12/2004	No	Not available	Not available	0%	0%

Sources: DoD (data); GAO (analysis and presentation).

Note: In this table the term "not available" means the GAO had not received sufficient data to make an assessment of the given program's design and/or technology maturity.

*Milestone I was a forerunner to Milestone A, the decision review that currently precedes the start of technology development.

^bProgram office projections.

^cCost growth is expressed as the percent change in program development cost estimates in fiscal year 2005 dollars.

Table 5. Program Data for 23 Programs Initiated under DoD's Revised Acquisition Policy (As of December 2005) (After: <http://www.gao.gov/new.items/d06368.pdf>)

3. Engineering

The previous sub-section captures various changes originating from engineering activities that affect requirements. Some overlap exists. However, the engineering

changes described here develop from engineering design analysis. This is a situation where the requirements lead to design complexity, problems, or compliance failure. Although technical analysis provides the basis for developing requirements, detail design engineering may provide greater accuracy.

The engineering sourced changes are the manifestation of design risk inherent in the ship specification development. There is a limit to the level and detail of analysis during the pre-CDR period. The complexity of ship design programs creates enormous opportunity for subsequent engineering changes.

In addition, there is a significant layer of changes, below the requirements level and within the detail design activity. They consist of changes to approved detail design products such as drawings and procurement specifications that do not require changes to the ship specification.

Procuring valves is an example where the specifications may permit various body materials, and the shipbuilder selects bronze. Later, it is determined composite bodies are preferred, so the procurement specification is changed. Such a change may require other modifications, to the detail design, to support the new material, and potentially to the ship specification.

Deficiencies in Government Furnished Information (GFI) or Contract Documents may also lead to design changes. Questions about GFI frequently result in the implementation of a newer version. The updated GFI usually includes some type of part number change at a minimum. Old parts are obsolete, or the vendor recently updated the system to a new and improved model, but provided the old information on the outdated system to meet contractual obligations. Any revision to pertinent design information discovered after contract award affects the shipbuilder's activities and is subject to a cost adjustment.

Engineering changes originate from both the Navy and the shipbuilder, the same as for requirements. By definition, the engineering changes occur post-CDR. As with requirements, engineering change has increasing potential for rework effects depending

on timing. Certainly, there is engineering and program management rework to effect the change along with the possibility of construction rework and sequencing issues.

4. Construction

Changes originating during the construction phase may come from planning or front line production. They include design improvements for performance or producibility, as well as identification of errors. At first glance, construction changes appear to have the greatest risk to rework since construction is in progress. In the case of design errors, this is true, but producibility changes generally are beneficial.

Error detection during construction is potentially the most complex rework situation. Depending on severity, the change could affect requirements, engineering, and planning/construction. The worst case is where the change requires all of the above and includes the need to rework completed work packages and re-sequence construction. The change may come from original requirements, detail design, manufacturing interpretation, or it may come from a production error.

Again, as for requirements, the Navy or the shipbuilder identifies the error or opportunity. Realistically, the expected changes from construction are due to design errors traceable back to requirements interpretation, deficiencies in GFI/VFI, or engineering errors.

C. EFFECTS

1. Cost

Pre-CDR changes are a component of the design development process. CDR entrance criteria require the design be ready to enter the detail design phase. The volatility, maturity, or readiness of the design is subject to interpretation. The Program Manager (PM) reports the readiness using appropriate measures and metrics to make the case for proceeding to detail design. There is obvious pressure to succeed, so there should be no surprise if changes are required immediately following CDR.

The real cost of pre-CDR change is elusive. Changes implemented before CDR are part of the design development contract. As mentioned earlier, the cost is not directly associated to the changes, but rather to the rate of changes as the program approaches CDR. Higher change rates indicate lower maturity and greater probability of post-CDR changes, which increase cost. In addition, lower maturity indicates a lower probability of fully concurrent design analysis, another reason to expect downstream changes with their additional cost.

Post-CDR changes receive varying degrees of processing based on the estimated cost. Formal changes process through an Engineering Change Proposal (ECP). ECPs themselves consume cost for research and analysis, as well as processing. They are funded typically through change management sections of detail design and construction contracts. These costs are more easily accounted for assuming they accurately reflect the impact of the ECP's programmatic cost.

Cost associated with design changes early in the shipbuilding process is generally limited to the change itself. However, when a change happens late in the program, a higher cost is incurred. This is because when the change occurs late in the program, in addition to the cost of the design change itself, there is an associated cost with rescheduling, re-planning, and re-scoping the amount of work and necessary resources required for the task. There is additional cost incurred due to an increase in the number of labor hours required to complete the change, as well as, any rework necessary on tasks already completed. If the change requires extending the schedule, additional cost growth could include increases in cost of overhead, inventory, material, labor, and associated inflation effects.

In addition to the cost of rework directly related to the design change, changes to any one system or component may potentially lead to changes in other systems resulting in the need for additional changes and subsequently additional rework. This is true in all phases of the shipbuilding process.

2. Schedule

Change affects schedule by creating additional work and, usually, rework. The magnitude of the schedule effect depends on the timing and complexity of the change. Changes can be absorbed into the design and production schedule as cost only. In most cases, the intricacy of the overall schedule allows disturbances that do not affect major milestones. However, it is important to understand that sequentially applied changes create convoluted schedule adjustments that have a greater effect together than separately. The aggregate effect may rise to a level where significant milestones slip.

A significant effect of design change is out of sequence work. When ship production occurs according to schedule, the production group builds the ship during the Execution phase of the Management Cycle. The test group starts testing in a stand-alone environment during this phase. If production progresses as scheduled, installation of equipment and systems is complete and ready for test during the Evaluation phase. The fact that the production group's work orders (bills) are zone oriented has no impact on test.

Adding in the design changes leaves the production group installing equipment and systems later during the Evaluation phase. The production group and the test group suddenly have competing goals. The production supervisor still has the responsibility of building the ship and production work orders continue to be zone oriented. However, the test supervisor needs to complete tests, and the tests are systems oriented. This is a shipbuilding paradox.

Since production work orders are zone oriented, the planning process usually allocates system installation across multiple work orders. If the production supervisor focuses on completing work orders, without concern for completing systems, the test supervisor cannot complete his goals. To support the test supervisor, the production group would have to work one or two items, on multiple work orders, to complete the installation of a system. The production supervisor may not consider this the most efficient method, and thus, there is a competition for resources.

In addition, it should be noted that a change in schedule has an impact on available resources to accomplish rework because of design change. The manufacturing process is carefully planned to ensure that the necessary skilled labor, equipment, and facility lay down spaces are available, when required, to support all programs under construction. As such, any change that results in schedule delays poses risk to other programs' schedules due to competition for resources. This typically results in excessive overtime, and rental or procurement of additional equipment.

Program schedules are politically sensitive territory. Rescheduling acquisition milestones is nearly impossible, and when required, is subject to rationalization. The aggregate effect of changes may not be recognizable in the cost accounting world of the program office. This does not reduce the criticality of change induced schedule effects. The most attractive solution for program managers is to convert the schedule impacts, due to change, into a cost.

D. CHAPTER SUMMARY

The opportunity for change, over the multi-year period of design development, detail design, and construction of naval ships is significant. Personnel changes, interpretations, technology, mission, regulatory, producibility, etc., all contribute to ongoing changes from Milestone A through delivery. The sources of change are an important input to analysis of change consequences and potential mitigation. Their impact is derived from accounting and budgeting submissions, and reports, as well as reference analysis.

Understanding the depth and breadth of design change implications is crucial to finding the real cost of rework. During any program phase, the consideration of a change initiates the cascade of inter-dependent effects that comprise the total cost of rework. The change proposal initiation kicks-off the change administration and change analysis. Groups indicating or realizing an impact provide estimates for the potential contributing costs.

Estimating in and of itself is a complicated task. Several factors make an accurate estimate nearly impossible. Add in the fact that production continues while the shipyard scopes the change and negotiates with the customer. The impact to concurrent functional and/or detail design continues to grow during change adjudication, requiring rework to implement. Planning and sequencing continue and then require rework to implement. Construction continues, requiring direct rework as well as related construction activities due to re-sequencing. Perturbation due to the change ripples throughout the program, greatly reducing efficiencies. It is questionable whether the change analysis and adjudication process is capable of comprehending the full extent and impact of changes to schedules and costs.

V. DESIGN CHANGE ANALYSIS

A. INTRODUCTION

A variety of analytical approaches was utilized to examine design change rework. They consist of cost, case, and chronological analyses. The cost analyses reveal how the programs are managed and reported. The case analyses investigates technology, effects on the ground, and management. The chronological analyses examine program phase budgets and design maturity. The intent of this approach is to understand the impact and relationship of design change rework at the acquisition level.

The actual cost of rework is proprietary to the contracted shipyard, and competition sensitive within the Navy. The cost analysis was derived from public acquisition level reports, data, and releases. The analysis attributes are inferred from the reference material and are not exact accounting figures; rather they are an informed estimate.

The analysis approach is expressly disengaged from formal cost accounting for several reasons. Actual accounting data is proprietary and this thesis is not. Cost accounting activities are complex and may not provide an accurate design change cost picture. Such inaccuracies are substantial enough to influence budget level numbers, as in the case of CVN 76 (GAO, 2005b). The combination of shipbuilding and accounting complexities' effects are not useful to this analysis.

Budget information was analyzed based on GAO reports related to shipbuilding programs. Related budget information from Selected Acquisition Summary Reports (SASR) was analyzed as a comparison. In addition, the allocations were evaluated for variability over time, in SASRs, Program Cost Breakdowns (Exhibit P-5), and Budget Item Justification Sheets (P-40). SARS are prepared annually and provide the current estimate of programs' cost, schedule, and technical status. Exhibit P-5, an annual budget submission, breaks down the program's budget over purpose and time. Exhibit P-40 provides individual program cost breakdowns.

Under the case approach, Technology Readiness Levels (TRL) were examined, for comparison, as a contributor to design change rework. A simulated scenario describes design change effects in the shipbuilding environment in order to enhance comprehension. Acquisition management and execution are examined for contributions and effects on the design change activity. The case analyses provide insight and comprehension of the design change rework issue.

Lastly, a time based program budget analysis displays how budgets related to engineering changes are modified through the various acquisition phases. In addition, design maturity is examined with regard to some extreme cases. Design maturity must be examined from a chronological perspective since its effects are related to the maturity at CDR. That is, maturity as detail design and construction begins. It is at this point that design maturity creates the most profound effects.

All of the analyses are intended to reveal the extent and magnitude of the design change rework problem, how well it is captured at the budgetary level, and significant contributors or indicators.

B. COST ANALYSIS

1. GAO Based Budget Level Data

A rough order of magnitude (ROM) approach to the cost analysis was selected to quantify the cost of design change at the ship's program budget level. The analysis includes inferred parameters for the base design change cost percentage rate (CBO, 2003), (Moosally, 2007), (Teel, 2007). The base rate is modified depending on lead ship status. The selected ship budget data is then evaluated individually, as class subtotals, and grand totals.

Shipbuilding programs contain an allocation for change orders. The change allocation varies by program from a low of 3% on current DDG 51s, to a high of 7% on LPD 17 (GAO, 2005b). It is reasonable to assume a lead ship would have a generally

higher allocation, but the program allocations are inconsistent with lead ships varying from 3% to 7% as well (GAO, 2005b). The allocated change order budget is expected to be low, with real expectations of from 10% to 15%.

The sources used for the budget analysis baseline are GAO reports oriented to understanding the causes and potential solutions to Navy shipbuilding programs' cost growth (GAO, 2005b) (GAO, 2007). Table 6 displays the budget data, baseline budget and budget growth due to construction, for a selected subset of ships (GAO, 2007). It includes an estimate of design change cost as a percentage of total budget aligned with the Allocated Change Cost budget.

Ship		Baseline Budget	Construction Growth	Construction % Growth	Estimated Change Cost	Estimated Change % Cost	Allocated Change % Cost	Allocated Change Cost
DDG 91		\$917	\$37	4%	\$95	10%	3%	\$28
DDG 92		\$925	\$62	7%	\$99	11%	3%	\$28
CVN 76		\$4,476	\$252	6%	\$473	11%	5%	\$224
CVN 77	L	\$4,975	-\$51	-1%	\$788	16%	5%	\$249
LPD 17	L	\$954	\$784	82%	\$278	29%	7%	\$67
LPD 18		\$762	\$246	32%	\$101	13%	4%	\$30
SSN 774	L	\$3,260	\$327	10%	\$574	18%	3%	\$98
SSN 775	L	\$2,192	\$294	13%	\$398	18%	4%	\$88
Subtotal		\$18,461	\$1,951	11%	\$2,805	15%	4%	\$811

Table 6. Selected Change Cost Analysis (\$Millions)

Removing CVN 77, with negative construction growth due to shifting of cost to another program, and LPD 17, with extreme growth, from the analysis in Table 7, does not materially affect the relationship of the Estimated Change % Cost to Allocated. The ratio is approximately 3.6 to 1. The analysis demonstrates the difference between formally Allocated Change % Cost and the Estimated Change % Cost and their relationship to budget Construction Growth.

Ship		Baseline Budget	Construction Growth	Construction % Growth	Estimated Change Cost	Estimated Change % Cost	Allocated Change % Cost	Allocated Change Cost
DDG 91		\$917	\$37	4%	\$95	10%	3%	\$28
DDG 92		\$925	\$62	7%	\$99	11%	3%	\$28
CVN 76		\$4,476	\$252	6%	\$473	11%	5%	\$224
LPD 18		\$762	\$246	32%	\$101	13%	4%	\$30
SSN 774	L	\$3,260	\$327	10%	\$574	18%	3%	\$98
SSN 775	L	\$2,192	\$294	13%	\$398	18%	4%	\$88
Subtotal		\$12,532	\$1,218	10%	\$1,739	14%	4%	\$495

Table 7. Revised Change Cost Analysis (\$Millions)

Although Construction Growth appears to consist of the difference between the Estimated and Allocated Change Costs, an analysis of a larger sample of ships, Table 8, indicates otherwise. In Table 8, an analysis of thirty-five ships, the Construction Growth is approximately equal to the Estimated Change Cost. Using the average Allocated Change of 4% indicates the ships' Budget Growth average of 11% significantly consists of design change cost.

The ROM analysis is consistent with expert opinion (CBO, 2003), (Teel, 2007). Lead ships experience approximately 15% real change cost and follow-on ships experience approximately 10%. The average Estimated Change % Cost is 12%. It is three times greater than the average Allocated Change % Cost of 4%. Why would the estimate be different? The true cost of design change is elusive and the allocated budget is targeted to the cost accounting representation of the individual changes, Engineering Change Proposals (ECP).

Ship		Baseline Budget	Construction Growth	Construction % Growth	Estimated Change Cost	Estimated Change % Cost
CVN 77	L	\$4,975	\$771	15%	\$919	18%
CVN Subtotal		\$4,975	\$771	15%	\$919	18%
DDG 100		\$938	\$142	15%	\$108	12%
DDG 101		\$935	\$62	7%	\$100	11%
DDG 102		\$1,016	\$126	12%	\$114	11%
DDG 103		\$1,107	\$56	5%	\$116	11%

Ship	Baseline Budget	Construction Growth	Construction % Growth	Estimated Change Cost	Estimated Change % Cost
DDG 104	\$1,062	\$97	9%	\$116	11%
DDG 105	\$1,184	\$42	4%	\$123	10%
DDG 106	\$1,233	\$27	2%	\$126	10%
DDG 107	\$1,089	\$21	2%	\$111	10%
DDG 108	\$1,102	\$18	2%	\$112	10%
DDG 109	\$1,138	\$21	2%	\$116	10%
DDG 110-112	\$3,505	\$29	1%	\$353	10%
DDG Subtotal	\$14,309	\$641	4%	\$1,495	10%
LCS 1-2	L	\$472	\$603	128%	\$172
LCS Subtotal		\$472	\$603	128%	\$172
LHD 8		\$1,893	\$320	17%	\$221
LHD Subtotal		\$1,893	\$320	17%	\$221
LPD 18		\$762	\$531	70%	\$129
LPD 19		\$1,064	\$228	21%	\$129
LPD 20		\$890	\$311	35%	\$120
LPD 21		\$1,113	\$283	25%	\$140
LPD 22		\$1,256	\$287	23%	\$154
LPD 23		\$1,108	\$337	30%	\$145
LPD Subtotal		\$6,193	\$1,977	32%	\$817
SSN 775		\$2,192	\$546	25%	\$274
SSN 776		\$2,020	\$154	8%	\$217
SSN 777		\$2,276	\$65	3%	\$234
SSN 778		\$2,192	\$246	11%	\$244
SSN 779		\$2,152	\$283	13%	\$244
SSN 780		\$2,245	\$41	2%	\$229
SSN 781		\$2,402	-\$24	-1%	\$238
SSN 782		\$2,612	-\$7	0%	\$261
SSN Subtotal		\$18,091	\$1,304	7%	\$1,940
T-AKE 1	L	\$489	\$44	9%	\$85
T-AKE 2		\$358	\$9	3%	\$37
T-AKE 3		\$361	-\$25	-7%	\$34
T-AKE 4		\$370	-\$32	-9%	\$34
T-AKE 5/6		\$683	\$20	3%	\$70
T-AKE 7/8		\$713	\$4	1%	\$72
T-AKE 9		\$380	\$9	2%	\$39
T-AKE Subtotal		\$3,354	\$29	1%	\$370
Grand Total		49,287	5,645	11%	5,934
					12%

Table 8. Change Cost Analysis (\$Millions)

Another way to look at the data is to accept the estimate that 50% of program cost growth, 11%, is due to design change rework (CBO, 2003), (Teel, 2007). That is 5.5%, which added to the average allocation of 4% equals 9.5%. Again, this is consistent with the expert opinion, which suggests an average of 12%.

The cost growth budget data indicates the design change cost is greater than the program allocations. Expert opinion and ROM analysis support each other and suggest the real cost of design change is three times the actual budget.

2. SARS Based Budget Level Data

A second approach to analyzing the design change cost uses Selected Acquisition Report Summaries (SARS) data from 1991 to present (DoD, 2007). Table 9 displays the budget data, baseline budget and program budget growth, for all available shipbuilding programs. Instead of an estimate of design change, the actual SARS Engineering Change Cost is presented. The Engineering Change % Cost is then calculated as a percentage of the baseline.

Program	Milestone	Baseline	Program	Program	Engineering	Engineering
		Budget	Growth	% Growth	Change	Change
					Cost	% Cost
CG 47	B	\$9,014	\$14,263	158%	\$981	11%
CVN 21	A	\$3,160	\$18	1%	\$266	8%
CVN 21	B	\$27,986	\$7,043	25%	-\$864	-3%
CVN 68	C	\$8,468	-\$2,228	-26%	-\$66	-1%
CVN 72/73	C	\$5,266	\$891	17%	\$0	0%
CVN 74/75	C	\$5,911	\$1,111	19%	\$0	0%
CVN 76	C	\$3,984	\$607	15%	\$36	1%
CVN 77	C	\$4,557	\$743	16%	-\$66	-1%
DDG 1000	A	\$1,754	\$6,307	360%	\$3,283	187%
DDG 1000	C	\$25,217	\$11,354	45%	\$3,706	15%
DDG 1000	A	\$31,548	\$4,474	14%	-\$841	-3%
DDG 51	C	\$16,954	\$45,799	270%	\$2,251	13%
LCS	A	\$1,173	\$766	65%	\$73	6%
LHD 1	B	\$2,932	\$7,069	241%	\$95	3%
LPD 17	A	\$61	\$13	21%	\$4	6%
LPD 17	B	\$9,018	\$6,594	73%	\$4,809	53%
SSGN	C	\$3,869	\$226	6%	\$7	0%

Program	Milestone	Baseline	Program	Program	Engineering	Engineering
		Budget	Growth	% Growth	Change	Change
					Cost	% Cost
SSN 21	C	\$20,120	-\$6,711	-33%	\$161	1%
SSN 21	B	\$20,120	-\$6,963	-35%	\$0	0%
SSN 688	B	\$5,127	\$22,964	448%	\$1,920	37%
SSN 688	C	\$5,127	\$22,936	447%	\$0	0%
SSN 774	B	\$45,633	\$47,375	104%	\$1,272	3%
Total		\$256,996	\$184,651	72%	\$17,026	7%

Table 9. SARS Based Cost Analysis (\$Millions)

The average Engineering Change % Cost is 7%. This is almost twice the average of 4% reported on selected programs in GAO-05-183. The difference is likely due to the 4% average based on individual ship data where the SARS analysis is program based. As well, the 4% is a directed average, not a reported budget average, as is the case with the SARS. Therefore, the SARS Engineering Change % is a better indicator of the actual budget than the GAO reported budget assignment.

3. GAO to SAR Comparison

The macro level proposed estimate of design change cost as a percentage of the baseline is difficult to verify with publicly available data. The SARS analysis indicates that budgeting activities approach an ongoing 7% average. The GAO reports an average planned change budget of 4%. Since the baseline budgets routinely overrun by an average construction growth of 11%, there is evidence the real cost of design change and rework is under budgeted and under reported. This is not an indictment or accusation of wrongdoing, but rather a question on whether current practices accurately reveal the cost of design change. The subject matter experts' estimates of 15% for the lead ship, and 10% for follow-on ships, are reasonable when compared to the budget data.

The DDG 51 program is a good source for examining design change cost in concert with the budget data. The lead ship of the class had a total change cost 16% of the baseline budget. (CBO, 2003) The ongoing average change cost for the follow-on ships is 4%. Close examination reveals that several ships experienced significant negative change costs due to reduced Government Furnished Equipment (GFE) costs (GAO, 2007). The

savings in change costs resulted from selecting a less expensive combat system. Therefore, the ongoing budget change averages are skewed lower. The budget experiences the benefits of benign changes leading to lower average change cost. This example illustrates the under reporting of budget change costs. The lower cost GFE, while a design change by definition, align more to a baseline adjustment that should be captured outside of the change budget.

Ultimately, the most important data point is the magnitude of design change cost to the baseline budget. The analyses results of 10% to 15% are a significant portion of the total program cost, and deserve scrutiny for improving future performance.

C. CASE ANALYSIS

1. Technology Readiness Level

Figure 18 presents an analysis of the Technology Readiness Level (TRL) based on data from Table 5, as an indicator of budget growth due to ongoing design change cost. This analysis of multiple DoD programs is exclusive of shipbuilding. The solid line depicts a linear trend analysis of the data points. An inverse relationship exists between the TRL and the budget development cost growth. This relationship is expected, as lower TRL would indicate an ongoing need to perform design change as the technology matures.

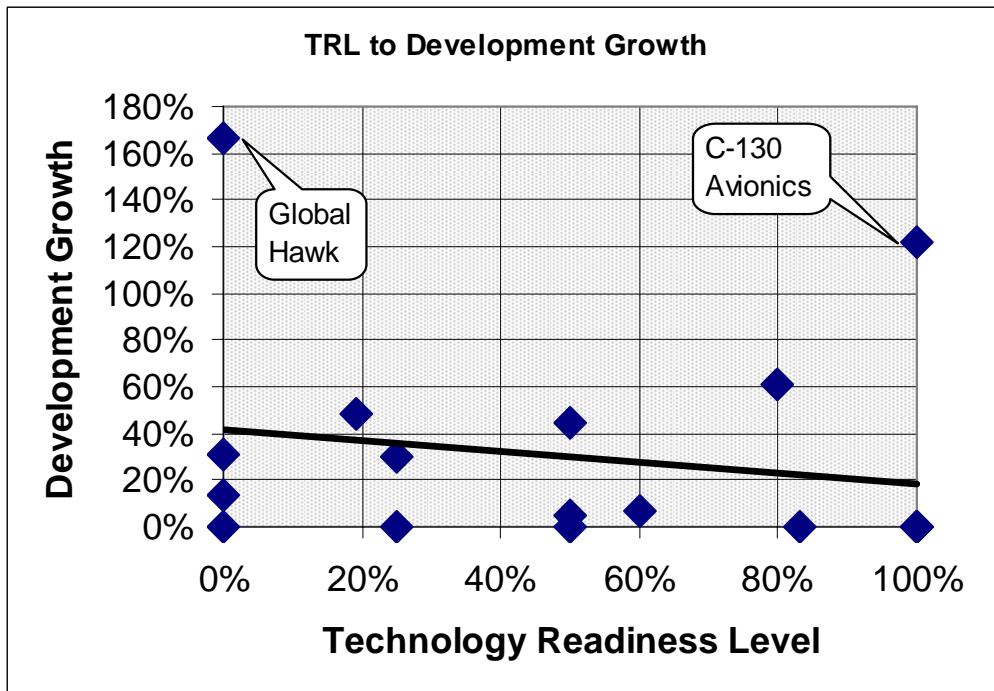


Figure 18. TRL to Cost Growth Analysis

The cost growth due to very low TRL averages 20% higher than the 100% TRL. Since the additional cost is primarily development, or design change, the 20% value roughly supports the 10% to 15% estimate used in the budget level analysis. The TRL analysis relates to the requirements maturity/volatility issue but is based on technology as a contributor rather than overall design maturity.

2. Simulated Scenario

Preliminary planning determines dates for key events at the time of bidding, prior to contract award. Key dates include keel laying, launching, and delivery. These dates are critical. The use of major resources, such as a dry dock, must be carefully coordinated when a shipyard is building multiple ships at a time. Although the schedule usually contains a little slack time, delays may force a ship to miss a particular window of opportunity, resulting in a domino effect across the yard.

For example, a government furnished system, still under development after contract award, may have a major impact to cost and schedule if equipment for that system is located in a compartment in the lower sections of the ship. Lower compartments must be completed in a manner suitable to accommodate compartment testing prior to float-off. In order to prevent rework, the major equipment in these compartments has to be installed by this time.

Depending on requirements, such as water-tightness and structural integrity, different types of compartment testing are conducted. A hull tightness test puts the compartment under air pressure in order to examine all fillet welded boundary connections and erection joints for leak detection. Any temporary access used for installing large equipment must be sealed prior to test.

In order to prevent rework, the documentation, as well as the equipment, must be available to support the design, planning, purchasing and construction activities related to this sequencing of events. Late product definition or lack of technical information has an ever-increasing impact depending on the system's equipment locations, as well as its interfaces. Detail design drawings affecting these lower compartments are required early in the schedule to support these activities.

For example, a system cable block diagram may kick-off the process, identifying the need for the system to other disciplines, and to facilitate purchasing the associated equipment, cables, etc. An arrangement drawing is required to specify the location of the system's equipment. Foundation drawings are required to define the structures fitted to support and secure the equipment to the main hull structure in a manner that resists deflections that could damage the device (SNAME, 1980). All of these require information in a timeframe that allows completion of the drawing by a certain date.

The same government system may have equipment in other compartments or interface to other systems on the ship. These systems' cable block diagrams, arrangement drawings, etc., are also dependent on information for the example government provided system. Therefore, lack of information affects multiple drawings, as well as the construction activities occurring in multiple areas of the ship.

The bid package, and consequently the contract, specifies the timeframe for the delivery of government furnished equipment and drawings required to support these design and construction efforts. The shipyard bases their estimates on these dates. If the delivery dates do not facilitate conducting detail design, procuring any required material, and completing the construction activities prior to the date required for compartment completion, the result is likely out-of-sequence-work and rework.

With the delivery date as the driving factor for the ship's schedule, drawings are scheduled to support construction of assemblies in a particular order. When a drawing is due for release, lack of information becomes an issue. The deficiency may only affect part of a drawing, with other parts being known. In order to complete as much of the design and construction activities as possible, drawing development proceeds, documenting missing information with reservations. This allows the use of known information, preventing an even greater disruption.

Some effects of the missing information are evident already. Even if the customer provides the information shortly after release of the drawing, at a minimum, the drawing will require rework to remove the reservations and add the missing information. This requires additional work effort from all parties involved in the release of this drawing. Affected areas include various design engineering groups, technical checkers, configuration management, document control, planning, and any other discipline linked to this drawing. The later the information is available, the greater the impact.

Failure to provide the information and/or equipment prior to construction of this lower compartment leads to completing the compartment and compartment testing without the equipment or possibly delaying this compartment's completion. Completing the compartment and installing the equipment later requires reinstallation of a temporary access. Besides the additional work of cutting an access hole, then resealing the hole after equipment installation, this voids any completed testing of the compartment. The compartment must be retested and this increases labor costs as well as schedule slippage. Due to the timing, the additional work scope has grown.

Waiting for the equipment could delay float-off. Depending on dry dock availability, delaying float-off could have a major impact on the shipyard's other projects. The other ships' may also have a specified timeframe scheduled for use of the dry dock. Missing any ship's window of opportunity may have serious consequences to the shipyard. Depending on the delay, the shipyard may chose to slip the timeframe for all of the ships, but more likely would reschedule this ship at a later available timeframe.

It is not easy to determine the potential impact of a delay. Several immeasurable advantages of having the ship in the water are lost. For example, accessing the ship after it is in the water is usually much easier than accessing it on land or dry dock due to the number of stairs required for the higher elevation on land. Some support services, such as power or telephones, may not be available while on dry dock.

The same situation, late product definition, could be the result of design changes or simply deficiencies in the information provided. If the contract specified a certain system, and changes to that system occurred after contract award, the result could potentially be rework. Again, depending on the timing of the change, the impacts increasingly cascade throughout the shipbuilding process.

Even minor design change is disruptive. Dealing with numerous changes adds a whole new level of complexity. So much so that Volume 4, Chapter 6, of the Contract Pricing Reference Guides contains a section specifically addressing cumulative impact costs. The complexity of the inter-dependencies in shipbuilding makes it almost impossible to determine the cumulative effect of modifications. As defined by the guide:

Cumulative-impact costs are costs that are unforeseeable or costs that were not readily computable at the time of an initial equitable adjustment. They typically occur as the result of an unanticipated loss of efficiency or productivity caused by numerous contract modifications on a single major contract. (Office of the Deputy Director of Defense Procurement for Cost, Pricing, and Finance [DP/CPF], 2000).

The guide's explanation of when the unforeseeable effect of numerous modifications warrant an equitable adjustment compares two case studies for reference. The Ingalls Shipbuilding case involved three shipbuilding contracts affected by several

thousand change orders, resulting in a 58 % contract price increase and a 4-year delay. The contract price increased from \$113 to \$209 million. The cumulative-impact costs from the Ingalls case were allowed (DP/CPF, 2000).

In comparison, the Dyson case involved 39 change orders, resulting in a 19% increase and an additional 100 days. The contract price increased from \$612,454 to \$3.3 million. The cumulative-impact costs from the Dyson case were not allowed (DP/CPF, 2000). The two cases are widely cited, and debated, with the goal of clearly defining cumulative impact. Unfortunately, determining if the impacts caused by multiple changes were unforeseeable will always be subjective to some degree.

Essentially, it comes down to pay for the services provided. If the contractor has started working on the job specified, after contract award, he expects to be paid for his services. If the customer changes the requirements of the job, via contract modification, making any or all of the incurred work obsolete, it does not absolve the customer from paying for services rendered. Unfortunately, the biggest challenge is accurately estimating the true impacts of the modifications.

3. Acquisition Handling

On July 24, 2007, in testimony before the Sub committee on Seapower and Expeditionary Forces, Committee on Armed Services, House of Representatives, Paul L. Francis, Director Acquisition and Sourcing Management Team stated that

...what we really need is a new paradigm for establishing programs and overseeing them, and I'd say that would consist of three things. One is a better business case. A real solid business case up front for programs. A good plan for making business arrangements and contracting on programs and a good plan for execution. And I think to curb the optimism of what we see in programs today, we really do need that solid business case up front which I would describe as from requirements, mature technologies, a knowledge based lay down of all the key events in design and construction. Coupled with metrics for goodness. It's one thing to lay the events down. It's another to have a set of metrics or criteria to know whether they make sense or not.

As reported in GAO report 07-943T, Navy shipbuilding programs are often structured around a business case that is not executable due to the desire to introduce immature technologies, late design stability, and unrealistic cost and schedule estimates. Case in point are the LCS and LPD 17 programs. These programs trace back to a flawed business case (GAO, 2007). Despite “significant challenges” in the design, the Navy proceeded with unrealistic schedules that resulted in continuous out of sequence work. This drove considerable rework, disrupted the optimal construction sequence, and affected the application of lessons learned for follow on ships in the program (GAO 2007). The GAO reports that both the DDG 1000 and CVN 78 programs are at risk for similar reasons.

Coupled with inadequate or often no business case at the start of a program, the Department of Defense Program Managers are not given the necessary authority to successfully execute acquisition programs. Studies performed by the GAO show that program managers cannot reject new requirements, control funding, or control staff. In surveys and subsequent interviews by the GAO, Program Managers attributed unstable requirements and funding, along with insufficient support from the DoD once a program begins, as their biggest obstacles in successful program execution (GAO, 2006b)

Between April 2004 and November 2005, the GAO conducted a case study that compares the DoD’s product development with commercial product development efforts. What they discovered was that the commercial industry took a holistic approach and

- Followed a rigorous process for short and long term strategic planning
- Followed an evolutionary development process that focused on market needs and not attempt to meet all needs at once
- Mapped product concepts requirements to resources to enable successful execution of a program within cost and schedule
- Matched the right people to the program
- Adhered to knowledge driven development decisions
- Empowered program managers to make decisions regarding program readiness, problem resolutions and implementation solutions
- Senior leaders set clear goals for the Project Manager and team with incentives for meeting those goals and Program Managers were held accountable for decisions made

- Senior leadership committed to the programs under development and encouraged communication and collaboration

Programs from commercial industries contributed their success to the support from their top leadership and to a disciplined approach to strategic investment, program selection, and execution driven by knowledge based processes. Figure 19 depicts the critical support and accountability factors that guide commercial product development.

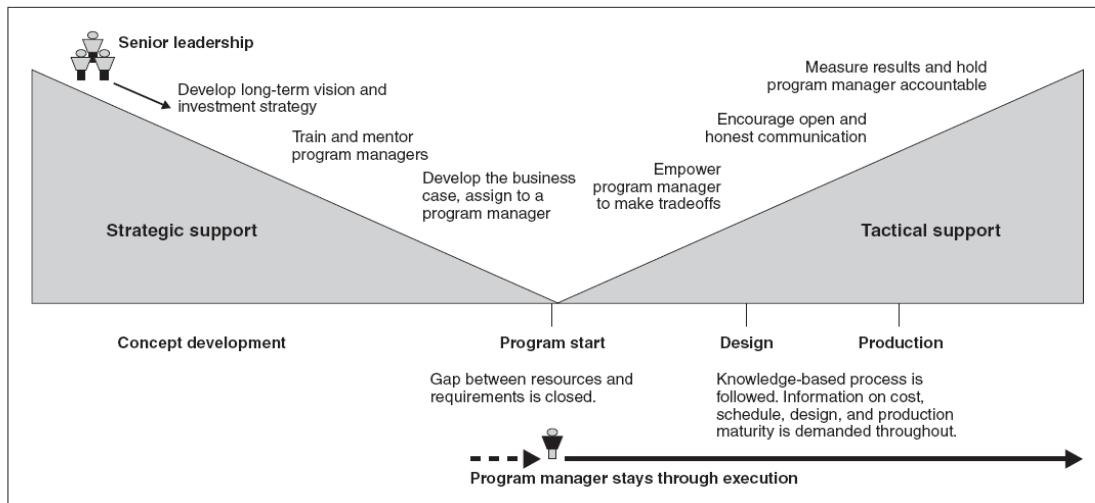


Figure 19. Critical Support and Accountability Factors (From: <http://www.gao.gov/new.items/d06110.pdf>)

Although senior DoD leaders attempt to develop short and long term strategic plans for US defense, this rarely happens. Unrealistic investment strategies do not ensure pursuit of the right program mix. In addition, DoD does not always ensure development of a realistic business case for new initiatives. Program managers are not fully empowered to manage programs once started, nor held accountable when programs falter (GAO, 2005a). DoD program managers, surveyed by the GAO, stated that users frequently requested new or improved capabilities as programs moved forward through the acquisition process. These additional requirements were usually not funded and the Program Managers felt they were not authorized to refuse the additions.

Program managers also indicated their belief that program decisions were made “based on funding needs of other programs rather than demonstrable knowledge” (GAO,

2005a, p.37). Furthermore, they felt they lacked necessary resources to provide program cost, schedule, and performance information to their leadership. They felt they were not trusted, nor were they encouraged to openly communicate and collaborate due to fear of funding adjustments, and they felt continued promotion of their programs was necessary to maintain commitment from top leadership (GAO, 2005a).

Table 10 highlights key differences between the best practices employed by leadership in the commercial industries and the DoD's way of conducting business. DoD Program Managers' comments, collected in GAO surveys, as well as follow-up interviews, suggest that while the DoD is proficient at developing long-term visions and strategic plans, it does not develop "integrated investment strategies" for weapon acquisitions to achieve planning goals. Consequently, more programs than can be afforded are initiated. This leads to competition between programs for funding, thereby promoting cost estimates and program capabilities that are not achievable (GAO, 2005a).

Best practices	DOD
Develop long-term vision and investment strategy	DOD has long-term vision, but not an investment strategy. Lack of investment strategy has created competition for funding and spurred low cost-estimating, optimistic schedules, and suppression of bad news.
Adopt evolutionary path toward meeting customer needs	DOD has adopted evolutionary development in policy but not in practice.
Match requirements and resources before starting new product development	DOD has encouraged achieving match in policy but not in practice. Requirements are not stable; funding commitments are not enforced; key technologies are not matured before development. Requirements and funding are biggest obstacles in view of program managers.

Table 10. Strategic Leadership Support Comparison (From: http://www.gao.gov/new_items/d06110.pdf)

Although some effort has been made to adopt processes supporting evolutionary development, significant increase in capability is still expected. DoD policy now encourages programs to match requirements to resources prior to program initiation. Instability in funding and requirements are still the biggest risk factors to program success (GAO, 2005a). Figure 20 illustrates the breakdowns in support and accountability in the DoD.

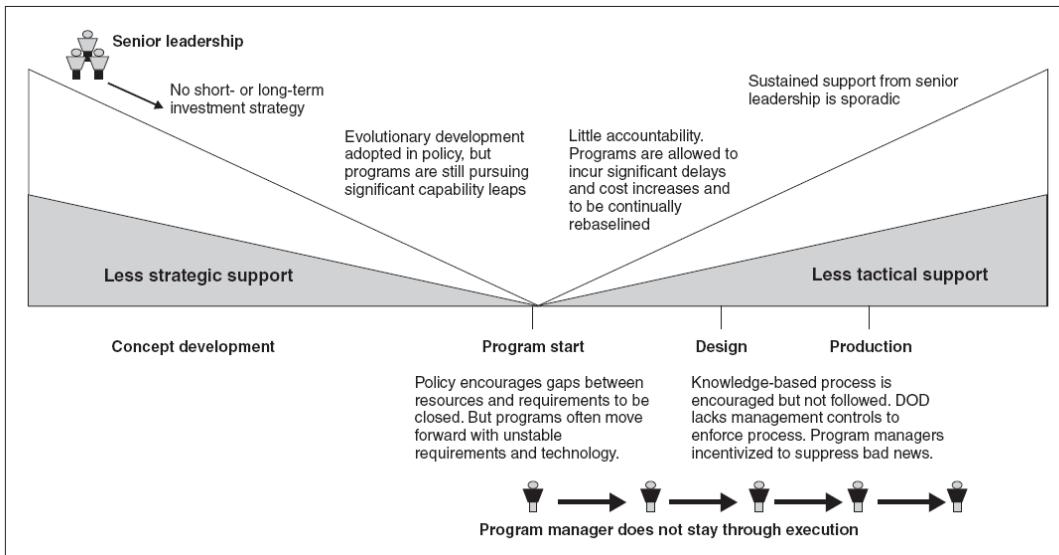


Figure 20. Breakdowns in Support and Accountability Factors (From: <http://www.gao.gov/new.items/d06110.pdf>)

The GAO revealed a number of problems with the acquisition process. For example, the DoD's acquisition policy encourages best practice for decision making such as technology demonstration, but does not establish any controls to ensure it is practiced. In some cases, programs can move into design, integration, and production phases prior to readiness demonstration. Without controls to ensure following the practice, the time and effort exerted to ensure utilization of a knowledge-based approach during decision-making processes, is a wasted effort. Table 11 highlights the difference between commercial industry and the DoD with regard to knowledge based development and accountability. The GAO derived this information from interviews of Program Managers, past reports, and observations made during the 2004-2005 study.

Best practices	DOD
Base decisions on quantifiable data and demonstrated knowledge	DOD policy encourages decisions to be based on quantifiable data and demonstrated knowledge, but not happening in practice.
Empower program managers to make decisions	Program managers say they are not empowered in the same way as commercial companies. They do not control resources. They do not have authority to move programs to next phases.
Hold program managers accountable	Difficult to enforce accountability.
Program managers stay through execution	Tenure has been lengthened, but program managers generally do not stay after 3 to 4 years.

Table 11. Knowledge Base Comparison Support and Accountability Factors (From: http://www.gao.gov/new_items/d06110.pdf)

The GAO has made recommendations in the past that DoD utilize analysis derived from preliminary design using system engineering tools. The knowledge capture should include completion status of engineering drawings, systems, subsystems, design reviews, stakeholder analysis of level of completion, and “identification of critical manufacturing processes.” However, the GAO reported that DoD acquisition programs continued to move forward and yet failed to demonstrate readiness to go. The GAO points out, in a recent analysis of major weapon systems, that only 42% had achieved design stability at design review and virtually none, either in production or nearing production, planned to ensure production reliability (GAO, 2005a).

Figure 21 illustrates the differences in how the commercial industry defines success in product development and how the DoD defines success in program acquisition. In the commercial industry, the measure of success is simply to maximize profit. This is achieved by delivering a quality product to market, at the right time, and at the right cost, by using realistic investment strategies to achieve results. It is not so simple in the DoD. The DoD defines success as the ability to deliver high performance weapon systems to the Warfighter. This is contingent on the ability to attract funding successfully, for the desired programs during annual appropriations. Program managers

are compelled to be over optimistic about schedules, cost and technology readiness to maintain political support and funding of their programs (GAO, 2005a).

	Commercial companies	DOD
Success	Sale to customer.	Attracting funds.
Means to success	<p>Strategic planning/prioritizing.</p> <p>Realism and candor.</p> <p>Early testing.</p> <p>Early redlights, greenlights based on demonstration.</p> <p>Collaboration and trust.</p> <p>Senior leaders are program advocates. Corporate research departments are technology developers. Program manager is executor.</p> <p>Single program manager is accountable for delivery.</p>	<p>Competition for funds.</p> <p>Optimism and unknowns.</p> <p>Late testing.</p> <p>Early greenlights; late redlights.</p> <p>Oversight and distrust.</p> <p>Program manager is often the advocate, technology developer, and executor.</p> <p>Multiple program managers are accountable for continuation.</p>

Figure 21. Key Differences in Definition of Success and Resulting Behaviors (From: http://www.gao.gov/new_items/d06110.pdf)

Oversight in the DoD adds an additional layer of difficulty and pressure to the acquisition process. Figure 22 shows a more streamlined approach in commercial industries visited by the GAO, as opposed to the many layers, both internal and external, that DoD program managers contend with. With the time required to deliver complex weapon systems to the Warfighter, the organizational structure of the oversight process can go through several changes of command. This causes priorities to change throughout the life of a program. Program managers repeatedly face challenges to obtain continued funding and support for programs under development.

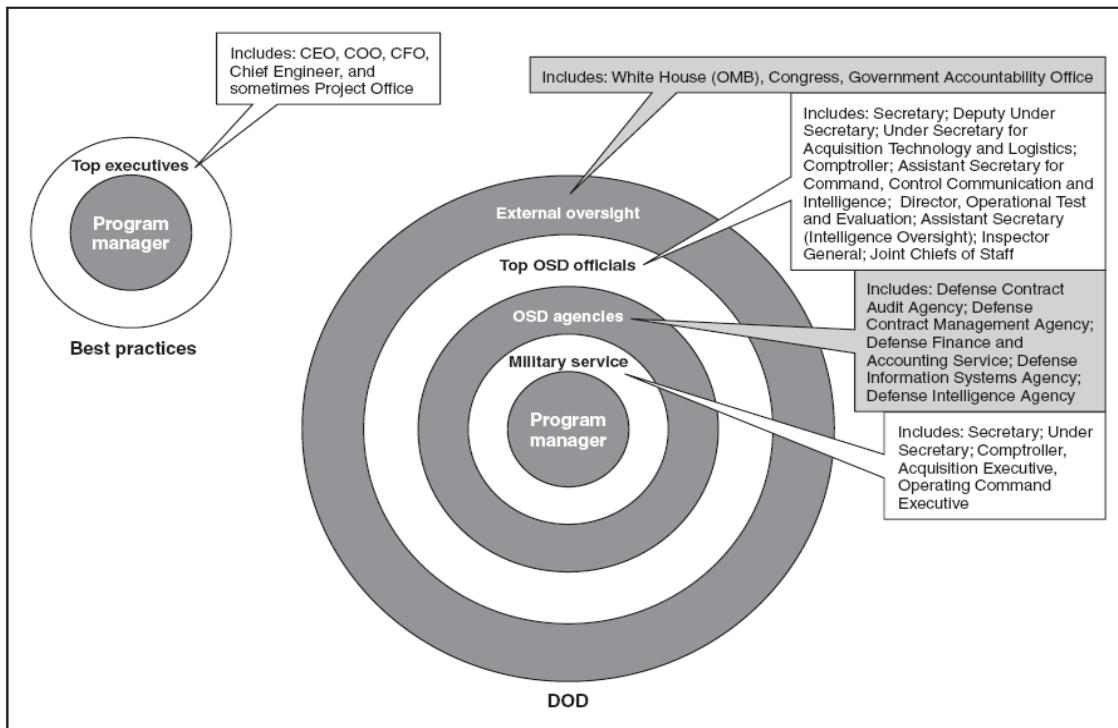


Figure 22. Commercial vs. DoD Oversight Environment (From: http://www.gao.gov/new_items/d06110.pdf)

D. CHRONOLOGICAL ANALYSIS

1. Program Phase

The SARS analysis to determine engineering change cost in relation to the baseline is supportive of reported cost by program phase. The SARS reports indicate the program phase for each line of budget data. Sorting and subtotaling provides the engineering change cost budget by phase in Table 12.

Program	Phase	Baseline	Program	Program	Engineering	Engineering
		Budget	Growth	% Growth	Change	Change
					Cost	% Cost
CVN 21	A	\$3,160	\$18	1%	\$266	8%
LCS	A	\$1,173	\$766	65%	\$73	6%
LPD 17	A	\$61	\$13	21%	\$4	6%
DDG 1000	A	\$1,754	\$6,307	360%	\$3,283	187%
DDG 1000	A	\$31,548	\$4,474	14%	(\$841)	-3%
A Subtotal		\$37,696	\$11,578	31%	\$2,785	7%
CG 47	B	\$9,014	\$14,263	158%	\$981	11%
CVN 21	B	\$27,986	\$7,043	25%	(\$864)	-3%
LHD 1	B	\$2,932	\$7,069	241%	\$95	3%
LPD 17	B	\$9,018	\$6,594	73%	\$4,809	53%
SSN 21	B	\$20,120	(\$6,963)	-35%	\$0	0%
SSN 688	B	\$5,127	\$22,964	448%	\$1,920	37%
SSN 774	B	\$45,633	\$47,375	104%	\$1,272	3%
B Subtotal		\$119,829	\$98,345	82%	\$8,212	7%
CVN 68	C	\$8,468	(\$2,228)	-26%	(\$66)	-1%
CVN 72/73	C	\$5,266	\$891	17%	\$0	0%
CVN 74/75	C	\$5,911	\$1,111	19%	\$0	0%
CVN 76	C	\$3,984	\$607	15%	\$36	1%
CVN 77	C	\$4,557	\$743	16%	(\$66)	-1%
DDG 1000	C	\$25,217	\$11,354	45%	\$3,706	15%
DDG 51	C	\$16,954	\$45,799	270%	\$2,251	13%
SSGN	C	\$3,869	\$226	6%	\$7	0%
SSN 21	C	\$20,120	(\$6,711)	-33%	\$161	1%
SSN 688	C	\$5,127	\$22,936	447%	\$0	0%
C Subtotal		\$99,471	\$74,728	75%	\$6,029	6%
Grand Total		\$256,996	\$184,651	72%	\$17,026	7%

Table 12. SARS Change Cost by Phase (\$Millions)

Each of the three phases has the same basic average Engineering Change % Cost of approximately 7%. Phase C is 6% and one would expect it to have the most change cost, yet unexpectedly, it is lowest. The shipbuilder labor cost experience expected in Phase C is represented in Figure 23. It depicts the rising effect as design changes delay past the start of production.

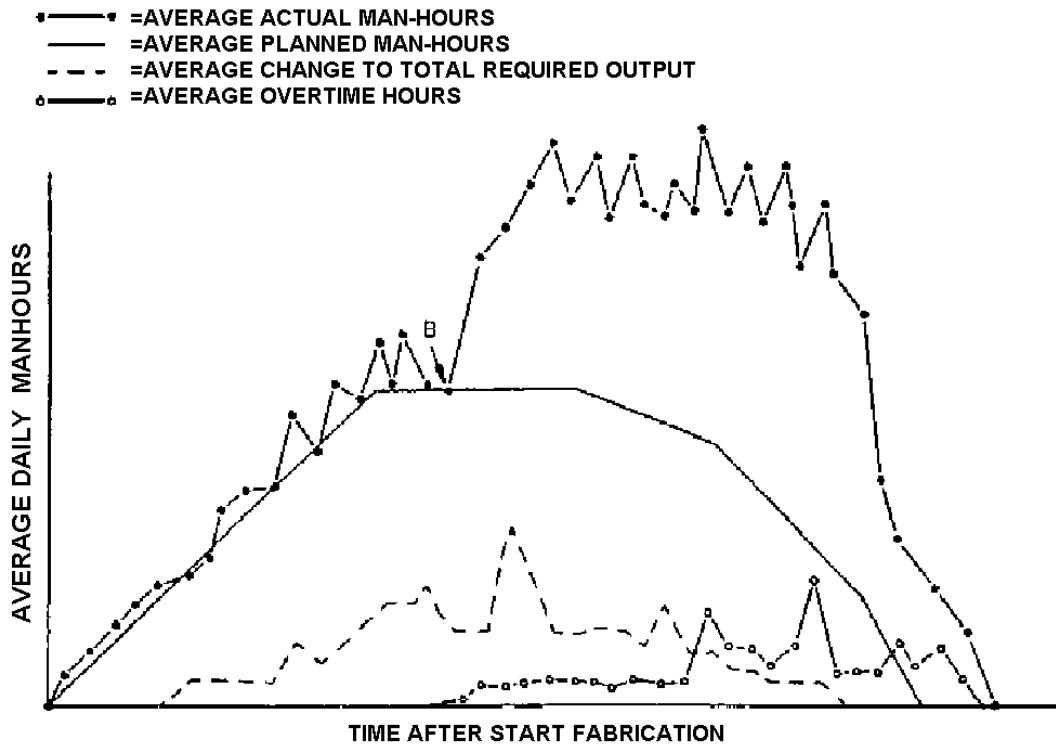


Figure 23. Shipbuilder Change Induced Labor over Time (From: Storch, 1995)

The relatively constant Engineering Change % Cost may either indicate that original estimates are correct, or that the budget is controlled over the effects of design change. Since the previous analysis and research indicate the budget is under reported, the phase analysis demonstrates the Engineering Change % Cost is not an accurate representation of the actual budget cost. In general, it is under reported, and managed, to maintain a constant relationship to the baseline.

An important point to note is most programs are re-baselined as they reach each milestone. The Engineering Change % Cost remains constant as a percentage of the current baseline, which is usually growing as the program passes through the milestones.

2. Design Maturity

There are two components of rework from the maturation of requirements. The first is the inherent, concurrent analysis used to resolve the effects of the change and gain approval from the appropriate change review board or authority. It occurs during the

change period, considered design development, and is not applicable to this study. The second is a post-CDR effect created by requirements volatility, or rate of change, that results in changes to resolve ambiguity or interpretations. The downstream changes essentially consist of design development cost indirectly deferred to the follow on period, post-CDR, due to lack of maturity and schedule pressure.

However, the maturity of the design at CDR has a significant cost effect. Research on the effects of requirements volatility displays it as a leading indicator of significant post-CDR change activity and program overruns. Earlier discussion on the cost of pre-CDR change as inherent to the program is accurate. For some programs, the maturity is too low, and therefore volatility too high, to carry on past CDR without severe negative effects on cost and change activity (GAO, 2005b). At some point, the volatility extends past construction start, or conversely the start is premature, greatly compounding the effect.

Requirements volatility exerts a disproportionate design change cost effect. There is no direct correlation between volatility measures and cost. The effect is identified by a short detail design period prior to construction start, or expert opinion on the technical maturity. Ships entering detail design or construction, with high requirements volatility, experience cost overruns in excess of the average by a factor of three or more. The percent of the baseline budget attributed to LCS 1-2 design changes is 36%, Table 8, and that of LPD 17 is 29%, Table 6. These estimates are much greater than the programs' budgetary 4% and 7% respectively. The requirements volatility effects are extreme and are a significant contribution to design change rework. Of all the contributing issues to design change rework, requirements volatility/maturity is by far the most influential.

E. CHAPTER SUMMARY

The layering complexities of acquisition management, ship design and construction, design change and rework, on top of accounting practices and requirements, makes financial analysis challenging. The effort to analyze the effects of design change

and rework on shipbuilding program costs without using proprietary or sensitive information requires a ROM approach. The analysis indicates the real cost of change is likely not conveyed by budgets or cost reporting.

The budgeted range of change cost allocations is 3% to 7%. Examining the effects of design change, requirements maturity/volatility, and budget analysis suggests the real cost is about three times greater, from 10% to 16%. The supporting analysis includes GAO and SAR budget data, TRL to cost growth, simulation, and SAR by phase. The budget and growth based analysis depict the growth experienced by shipbuilding programs and the expected contribution of change. Experts attribute nearly 50% of cost growth to change activity (CBO, 2005), (Teel, 2007). All of the examined sources indicate the proposed estimates are reasonable.

This is a significant level of cost and important to understand. The average cost of ships today is approximately \$1.1 billion. 10% to 15% of that cost is \$110 million to \$165 million per ship. For a mature ship design, without significant changes, like the DDG 51 class, it is enough to pay for nearly half a new ship. When the DoD acquisition community searches for opportunities to lower costs, they generally look to performance, rather than drivers. One could argue a number of justifiable reasons for design change, but the cost must be recognized and accounted for.

Research indicates a significant amount of the design change cost comes from requirements as well as DoD imposed regulations (CBO, 2005). Since this cost is actually incurred post-CDR, it demonstrates the design is not fully mature prior to detail design and construction. Design maturity, or requirements volatility, was shown separately as a potentially powerful driver of excessive cost growth due to design change rework. When examining program technical aspects for opportunities to save cost, the design maturity must be at the top of the list. The design maturity is a driver that no Program Manager or shipbuilder can overcome. Moreover, past a certain point, it has a disproportionate effect on design change rework cost and program cost growth, as in the case of LCS and LPD.

Management of design change emerges as the most controllable component of cost. Like most business situations faced by modern companies, management is the key

to success. This is true also for DoD acquisitions. The shipbuilding acquisition and technical management, from the DoD down through the Program Management Office, the shipbuilder, and ultimately the frontline supervisor, all have a role to play in comprehending the full scope impact of design change rework. They must operate with a priority goal of minimizing, and controlling the initiation and conduct of design change.

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VI. CONCLUSION

A. INTRODUCTION

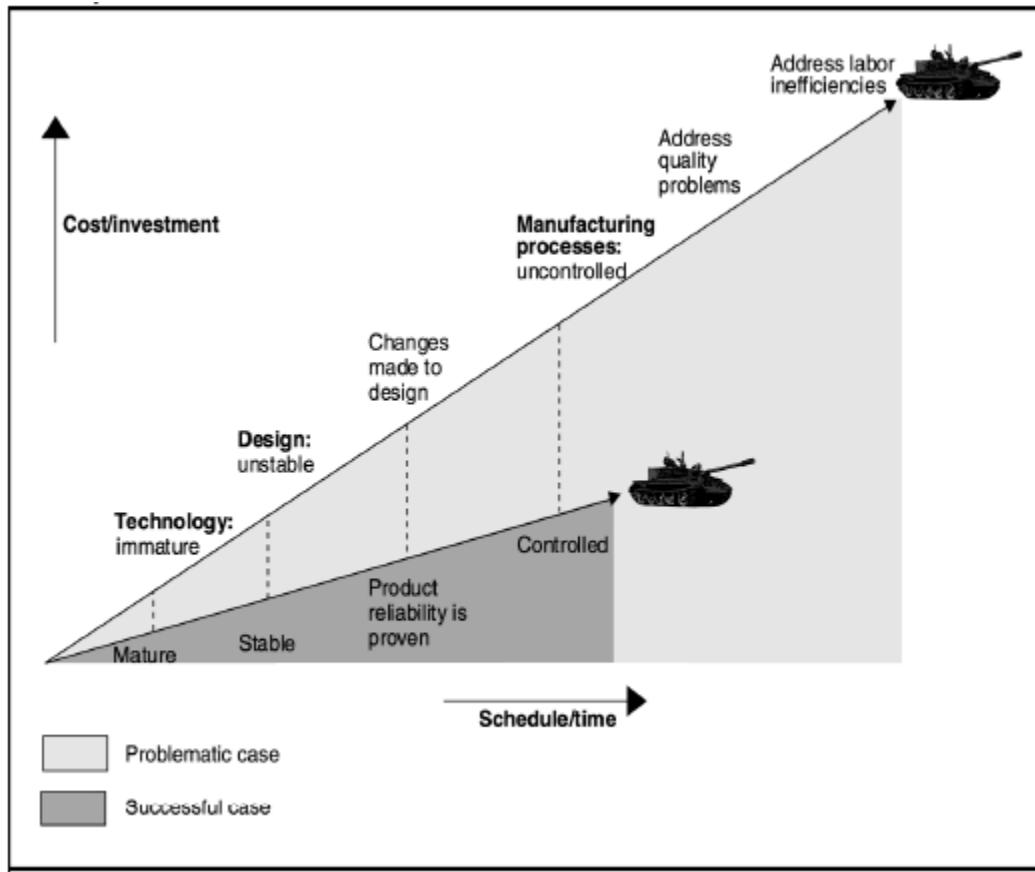
Analyzing Naval Shipbuilding projects from Milestone A through system development, construction, and delivery, provides insight into the complexity of the time phasing and interdependencies of program and contractor activities. Adhering to the DoD Acquisition System process, by meeting the requirements for each milestone and decision point, should provide an effective, affordable solution, producible in a timely manner. This being the primary objective of Defense acquisition, one would not expect design change prior to the ship's delivery.

Unfortunately, many of today's programs are plagued with design changes. Issues identified point to poor execution of the policies and procedures. Several examples of incomplete or ambiguous requirements indicate a failure to follow the process. Bypassing exit criteria and key decision points for each phase often occurs in the name of new technology. The success of each phase depends heavily on the quality of the decisions and deliverables from the previous phase. Sidestepping key decision points or allowing insufficient/ill-defined requirements has an increasingly negative effect on follow-on phase performance.

These deficiencies often start a sequence of events that result in rework. The use of immature technology or incomplete/ambiguous requirements leads to an unstable design. Unstable design leads to design changes. Design changes lead to out-of-sequence work and uncontrolled manufacturing processes. The GAO illustrates quality problems and labor inefficiencies, due to lack of control, in Figure 24 (GAO, 2002). Programs with numerous changes indicate that at least portions of the design were unstable prior to contract award.

The thesis research addresses deficiencies in execution of the acquisition process and finds them closely related to rework resulting from design change. Figure 24 illustrates the notional impact to cost and schedule due to unstable design vs. stable

design. The impacts leading from the use of immature technology is in stark contrast to the controlled environment and stable design facilitated by the use of mature technology (GAO, 2002).



Source: GAO's analysis.

Figure 24. Notional Illustration Showing Stable vs. Unstable Design (From: <http://www.gao.gov/new.items/d02701.pdf>)

Design changes are inevitable. They may be the result of efforts to provide an improved solution or the correction to an existing deficiency. Project managers frequently identify change as the major cause of program failure. This chapter reviews key points associated with design changes leading to rework and proposes modifications and improvements to existing shipbuilding and Navy practices. Balancing the objectives of the goal to provide to the Warfighter, battle space dominance, while keeping the overall cost low enough to allow consistent purchase of additional ships, requires a concerted effort by all parties.

B. SUMMARY OF KEY POINTS

Following the Systems Acquisition process provides a good start to executing a successful program. The requirements for each milestone and decision point must be satisfied and the deliverables for each phase complete and concise. Anything less starts a chain of events resulting in design change, one of the major causes of rework.

1. Major Causes of Rework

What are the major causes of rework? Rework is the act of redoing, correcting, or rebuilding. Design change is considered the largest contributor to rework, and often causes out-of-sequence work. Out-of-sequence work reduces efficiencies and may result in more rework. Based on the definition of rework, the thesis finds two different situations as major contributors to rework.

The first consists of design changes, where a contract modification replaces a previously specified item or system with a different item or system. This usually occurs due to technology obsolescence or the introduction of an improved capability. The second situation consists of errors and omissions in the contract documents, specifications and/or supporting government furnished information. Resolving this lack of information usually requires additional work effort by the contractor and is therefore design change.

In either case, changes invoking additional work effort by the contractor require a contract change and equitable adjustment. The equitable adjustment should address payment for work already accomplished by the time the change is authorized or a stop work is put in place. Unforeseen consequences often generate extra rework because of the changes. The interdependencies of the ship design and construction process almost guarantee additional rework when anything other than what is scheduled occurs.

2. Reducing Requirements Volatility and Resulting Rework

How can requirements volatility and associated rework be reduced? Requirements volatility is a potentially explosive contributor to design change rework. The

consequences of proceeding with an immature design at CDR are too great to overlook. The expectation of a high maturity level at CDR is critical to reduce the chances of extreme effects. The DoD 5000 process should include greater clarity and require a high level of approval in order to ensure a mature design and to prevent significant ongoing change.

To prevent the excessive effects encountered by the LCS or LPD programs, the Program Manager and shipbuilder should strive to reduce requirements volatility, approaching CDR, as it translates to lower design change rates. In fact, requirements volatility should be eliminated in the run up to CDR. This can be accomplished by managing the design toward modularity and subsystem independence. Taking steps to promote a stable and robust design improves the likelihood of reduced changes, and provides greater accommodation of directed changes.

The entire period following Milestone A is the best place to promote design stability. Pushing the high-level solution of functional requirements, early and with zeal, leads to less churn and a quicker design. The Program Manager has the ability to influence the direction of the technical solution toward stable, elegant, and simple design that matures before the need to evaluate at CDR.

3. Reducing Design Changes after Start of Detail Design

How can the quantity and cost of design changes after start of detail design and construction be reduced? The timing of the design change has an increasing direct effect on the potential impact to cost and schedule. Depending on the stage of the ship design and construction process, the resulting rework may be a simple change to a drawing or the drawing change followed by a complete rip-out and replacement of the equipment or system. Depending on the area of the ship impacted, the change may include a requirement to cut new access holes. In extreme cases, this could mean a return to dry dock.

A closer investigation provides insight into the true causes of design change and potential areas for improvement. Design change is most evident when a previously specified item or system is revised to a different item or system through some type of

contract modification. The change could be customer or contractor driven. It may be motivated by the desire to incorporate an improved technology, or simply the correction of a design deficiency. As in the case of LCS 1, new rules and regulations may be imposed after contract award.

Design change in one area may lead to the need for design change in another area. Several factors contribute to the potential impact resulting from the change. A few examples to consider are:

- The timing and magnitude of the change (Impact to schedule?)
- Whether the system is stand-alone or tightly integrated with other systems (Impact to other areas/systems?)
- How much of the original work is already or will be completed by the time the change is negotiated and implemented (Rip-out, re-test?)
- When will the change be implemented (Stop work or risk additional rip-out, retest?)

The contractor is compensated for any/all of the original work completed prior to a stop work order or the negotiation and authorization of the change. This adds an additional layer of complexity. In most cases, the status of in-process work is fairly subjective. The whole process of installing equipment only to rip it out later generates waste of time and money, not to mention negative consequences to quality and employee morale.

The acquisition process should proceed with stable design only. This does not mean the project should be cancelled or delayed when the desired technology is not available. It means reducing the risk of rework by specifying only mature solutions in the contract. Reserve space and weight in all cases where design depends on immature technology.

Additional design development will be required once the design is mature and the information is available. Reserving space and weight, as opposed to providing incorrect information for an unstable design, reduces any chance that the shipyard purchases erroneous material and installs it on the ship. This reduces some of the cascading effects of rework. It also lessens the impact to quality and craft morale.

4. High Cost of Out-of-Sequence Work

How to provide the latest and greatest technology without incurring the high cost of out of sequence work? Consider the contracting of a house as a simple scenario used to explore rework and the high cost of out-of-sequence work. The owner requests the contractor build a house, providing specific requirements such as desired square footage, number of bedrooms and bathrooms, type of exterior, etc. The house must be complete within six months of signing the contract. The contractor provides a proposal based on the owner's specified requirements and floor plan or general arrangements. A contract is signed once the owner and contractor agree on a price.

The contractor, now under contract, develops detailed plans based on the contract documents reflecting the owner's requirements. The details include such items as what color to paint each room, type and color of flooring, etc. The owner may have specified a particular wall color, or in the absence of specification, the contractor may submit a request for information.

The contractor schedules the construction activities in a particular order to facilitate efficient use of resources and to prevent interference or disruption that would jeopardize the required completion date. When the time comes to paint a particular room, the contractor schedules the painter. The painter preps the room for paint, taking precautions to prevent any undesired impact to other areas of the house. For efficiency sake, the contractor schedules the painter prior to installation of any fixtures or flooring.

A few months after the painter completes the task, the owner decides the room should be a different color. By this time, the flooring is installed. Initially, this may seem like a minor change. If the original cost to paint the room is x , then it should cost x to paint it again. However, the situation has changed and is still changing. The schedule is tight and the completion date is fast approaching. The contractor is ready to schedule the installation of fixtures.

The change procedure requires that the owner submit the change request for proposal by the contractor. The contractor receives the request. Determining the impact of the modification is no simple task. If the owner did not request a stop work, the

contractor has two choices. He can follow the schedule or delay work in the area impacted to prevent additional disruptions. The time it takes to scope and negotiate the change may render the risk of a delay infeasible.

Without a stop work, the contractor will most likely follow the schedule and install the fixtures on the chance that the owner will not accept the bid and cancel the change. This removes any added risk on the contractor's part of missing the deadline. Unfortunately, the cost of any change not yet authorized continues to grow as the original work is completed. In this case, the cost growth consists of the additional rework now required to remove and replace the fixtures prior to painting if the change is implemented.

Other considerations for impact include the fact that flooring was installed and will require special protection. The current color is hard to cover and will require additional prep. Using the Reasonable Cost Approach, the contractor calculates the net cost of the contract modification as follows (Office of the Deputy Director of Defense Procurement for Cost, Pricing, and Finance [DP/CPF], 2000):

$$N = A - D + C$$

where:

N = Net change in cost related to contract modification

A = Current estimate of the cost to complete added work

D = Current estimate of the cost to complete deleted work not yet performed

C = Actual cost of all deleted work already performed.

The current estimate of the cost to complete added work, A, is now 2x due to the additional prep work, removal and replacement of fixtures, and special protection of the flooring. The current estimate of the cost to complete deleted work not yet performed, D, is \$0 because the task to paint the room to the original specified color has already been completed. The actual cost of all deleted work already performed, C, is x, the cost to paint the room the original specified color. The net change in cost related to contract modification, N, is:

$$N = 2x - 0 + x = 3x$$

In the sample scenario, the contract modification is three times the cost of the original work due to the timing of the change and the resulting out-of-sequence work. If the owner changed the color prior to the initial paint, the cost would have been substantially lower. Often what seems like a minor change has a ripple effect leading to significant unforeseeable disruptions to both cost and schedule.

Volume 4, Chapter 6, of the Contract Pricing Reference Guides provides an example of unforeseeable impacts resulting from just one modification (DP/CPF, 2000). In the Penner case, the government directed the contractor to change the method of pile driving under a construction contract due to potential damage to adjacent property. The contract modification required the contractor use water jetting instead of steam-activated pile driving. The contractor took reasonable steps to handle large amounts of water but was still overwhelmed by the actual amount of both water and mud.

The disruptions resulted in out-of-sequence work and considerable delays to the project schedule. The guide cites the Government as the responsible party for the unanticipated issues, due to the directive requiring jetting as the method of work. Out-of-sequence work should be avoided if possible. It inevitably leads to disruptions and rework which are both detrimental in terms of cost and schedule.

All effort should be made to prevent design changes. If design changes are required, a stop work should be put in place immediately to prevent the cascading effect of rework, waste and out-of-sequence work. The shipbuilder's processes should support potential growth by making efficient use of ship space. The production support system should provide the means to anticipate and manage out-of-sequence work.

5. Concurrent Technology Development and Production

Is it more cost effective to proceed with an unstable design or delay the start of design and construction? A primary cause of out-of-sequence work is the use of immature technology. The acquisition community accepts the additional risk with the intent of developing the technology while developing the product. Lack of information

usually accompanies lack of technology maturity. The deficiency of information or other resources required at a specific time may lead to out-of-sequence work and ultimately rework.

In order to provide the latest and greatest technology, the acquisition community often bypasses rules or guidelines designed to prevent the use of immature technology (GAO, 2006b). They justify the additional risk as a worthy trade-off for the capability gained. Moving forward with immature technology introduces instability and risk into the program.

Not only is the technology not available at the onset of the program, but the documentation required for detail design is often missing or incomplete. Drawings defining the equipment's footprint or power requirements are usually required early in the program. This is especially true if the equipment is located in a lower assembly where early removal of access holes is required.

As stated earlier, it is more cost effective to delay the start of the detail design and construction of unstable systems until the technology and supporting information are developed. Reserving space and weight informs the contractor that a change is forthcoming. The contractor can plan for the growth without having to act on bad information specified as a placeholder in the contract.

6. Acquisition Process – Event Driven vs. Schedule Driven

Is it more cost effective to use an event driven or schedule driven process? A disciplined acquisition process is essential to the success of any program. This must be a joint effort between the customer and the contractor, with investment strategies and business cases developed prior to program start.

Inadequate and/or ambiguous requirements definitions, along with weak or non-existent processes for evaluating requirements, signify a recipe for disaster. Realistic requirements must be established early with a rigorous process in place. Evaluation criteria should allow for the elimination of non-value added requirements and/or design changes that will place a program at undue risk.

Due to funding and the demand for Operational Capability, programs tend to lean toward a schedule driven process. Several studies show that event driven scheduling reduces risk to a program by ensuring that technology and process maturity are demonstrated prior to each follow on event. In a 2002 report on best practices, the GAO stated that “DoD’s acquisition policy establishes a good framework for developing weapon systems; however, more specific criteria, disciplined adherence and stronger acquisition incentives are needed to ensure the timely capture and use of knowledge and decision making” (GAO, 2002). The thesis research finds this to be true.

The acquisition process consists of well-established policies and procedures. Problems occur when the process is not consistently followed. Fear of losing program funding due to early identification of issues is a primary factor in the failure to execute the programs consistently. Therefore, the focus is on meeting schedules as opposed to achieving events necessary to move effectively to the next step.

C. LESSONS LEARNED/HEURISTICS

The most significant lesson learned from the rework research is the potential for excessive design change due to requirements volatility. Proceeding to detail design and construction with an immature design poses an extreme risk. Oversight provides one method for preventing this problem. However, a more proactive approach involves looking at where and how the design originates.

**Heuristic: The beginning is the most important part of the work
(Plato, 4th Century BC).**

The early work to develop the design is a leading indicator of design stability and maturity at CDR. The initial stages of concept development and system design set the stage for success and cost. This period is extremely sensitive to design choices as they shape further concept and design creation. If requirements specify building a house from rock, then further design becomes restricted to determining how to use the material. The goal, then, is to strive for design maturity and stability well before committing to detail design and construction.

Heuristic: The majority of the cost is determined in the early phases of the program (Systems Engineering Wisdom of the 1990s).

1. Defense Acquisition Process – Inconsistent Execution

The Department of Defense Directive (DoDD) 5000.1 defines the Defense Acquisition System as “the management process by which the Department of Defense provides effective, affordable, and timely systems, to the users” (DoDD 5000.1, 2003). The directive contains various policies aimed at meeting this objective. These policies govern the Defense Acquisition System.

The framework guiding the process consists of milestones and decision points with phase specific entrance and exit criteria. It allows Milestone Decision Authorities (MDA) and Program Managers some tailoring of program strategies and oversight in order to provide flexibility and promote innovation. The exit criterion for each phase seeks to prevent program risk by holding the program accountable for effectiveness, affordability and timeliness.

Accountability of these three items is an iterative check throughout the acquisition process. The eventual success of the program depends on each. Failure to meet any of these constraints puts the program at risk and at a minimum, raises the risk of requiring design changes. With such a process in place, it was surprising to find program after program lacking in at least one of these areas.

**Heuristic: Discipline, Discipline, Discipline (Douglas R. King, 1991)
(Maier & Rechtin, 2002).**

Specifying a system in the contract and then changing that system prior to delivery indicates some type of failure during the acquisition system process. If the system was effective, affordable and could be developed in a timely manner, why would it be ripped off a ship prior to ever being used? What makes an effective system at contract award suddenly become ineffective and how often does it happen? The answer seems to be that the selected solution did not adequately meet the acquisition system criteria.

Most changes drive up cost, so changes to resolve affordability issues after contract award are unlikely. Technology development concurrent with product development may encounter unforeseen set backs. Acceptable timeframes prior to contract award no longer supports the scheduled ship design and construction activities. An examination of major causes of rework points to the failure to meet any one of these criteria.

Knowledge-Based Acquisition is listed as one of the additional policies in Enclosure 1 of DoDD 5000.1. It specifies that the PM will “reduce technology risk, demonstrate technologies in a relevant environment, and identify technology alternatives, prior to program initiation” (DoDD 5000.1, 2003). The PM is to provide knowledge about key system aspects at specific decision points in the process. Even though this policy relates directly to the technology readiness level of a product, it does not specify any measurable criteria.

Heuristic: Define how an acceptance criterion is to be certified at the same time the criterion is established.

The use of immature technology in the development of a program is a widespread issue. The uncertainty of developing the technology while developing the product violates the timeliness objective at a minimum and depending on the time of final implementation, most like the affordability objective too. Programs using immature technology usually incur changes in requirements and funding after the program begins. PMs credit changing requirements and unstable funding as their main impediment to success (GAO, 2006b).

Recent changes in acquisition law require the DoD to certify that technology has been demonstrated to a specified minimum maturity level prior to use for system development (GAO, 2006b). This law represents a best practice that facilitates predictable program outcomes. Cost growth of programs using mature technology typically averages 5 %. In contrast, programs using immature technology experience around a 35 % cost growth (GAO, 2006b).

Proceeding with immature technology adds risk to both cost and schedule. The lack of information makes it hard, if not impossible, to develop a sound business case. This provides another example of bypassing the requirements of the acquisition system. Failure to execute consistently the acquisition policies and procedures is well documented. The follow on detail and construction activities fully depend on the quality of deliverables from this process.

2. The Shipbuilding Design and Construction Process – Too Rigid for Design Changes

The shipbuilder is in business to make a profit. Unscoped system or subsystem impacts, resulting from design changes, chip away at that profit. To prevent the possibility of uncompensated work, strict adherence to the contract and schedule is important. Capturing all impacts driven by customer specified design changes is equally important. This strict adherence sometimes leads to rework and waste. Unfortunately, neither the shipyard nor the customer ever really knows the full impact of the changes.

The primary bulk of design changes result from customer driven activities. An initial review of contract documents and GFI provides an opportunity for the contractor to question any obvious deficiencies. In several cases, the time required to discover a deficiency and authorization implementation does not support corrections prior to impact of detail design.

Deficiencies are required to be documented in a formal process and submitted to the customer for resolution. The customer researches the problem and provides a response. If the response entails additional work by the contractor, a contract modification is required. All of this takes time. The contractor's schedule contains minimal slack time.

The customer prepares the contract modification and submits it to the contractor with a request for quote. The contractor scopes the change and provides a response to the proposal, followed by negotiations with the customer. With the design and construction

activities so tightly scheduled, the contractor usually continues as planned, with the information provided. In other words, without a stop work order in place, the contractor develops the detail design drawings using the suspect data or GFI.

Sometimes the customer specifies a system as rollover, or the same design from a previous ship. In reality, the customer knows there will be changes, but the technology is in development and the documentation for the new system is not available to support detail design. Informal discussions between the customer and the contractor hint about the new technology, but the contract specifies the legacy system.

The schedule does not allow the contractor to gamble on the possibility of a contract modification for the new technology. The system may require long lead material or be tightly integrated to other systems on the ship. Out-of-sequence work may result in an additional cost. Without the customer directing the change or a stop work, the contractor would assume the risk of not meeting milestone dates.

Unfortunately, the time it takes to process change often extends past the detail design phase and well into construction. This means ordering and possibly installing equipment, cables, etc. for this legacy system onboard ship. All of this occurs even though the customer and the contractor are in the process of modifying the contract for the new system. Why allow such waste?

Both parties identify the risk of the change not being approved as justification to continue activities based on the original contract. Since the customer did not initiate a stop work, the contractor proceeds with the contractual direction provided. As the original work is completed, the cost of the increase grows in direct correlation with the time it takes to authorize implementation of the change.

The situation of specifying an unstable design adds risk to the contract. The contractor did not specify the unstable design. The goal of the acquisition system should be to manage risk, not shift the risk to the contractor. Nevertheless, at the same time, the contractor should seek practices that allow some flexibility to accommodate waiting for improved technology within a reasonable timeframe.

In addition to schedule limitations, the actual implementation of the design seems inhibitive to change. The arrangement of equipment, piping, cables, etc. tends to consume any available space set aside for growth. All disciplines should exercise efficient use of the ship's space in anticipation of changes.

A model showing the optimal sequencing of ship construction activities and the impacts of changes to that sequence could greatly benefit decision-making. The desire to outfit the ship with the latest and greatest technology often results in major design changes late in the construction phase. A model may help the acquisition community make wise choices about which changes are worth the cost and which are not. It may also provide insight in setting up the sequencing of work to minimize these types of interruptions.

D. RECOMMENDATIONS

1. Change Management

First and foremost, all parties must realize that change is necessary and must be managed in a systematic, structured process. Preventative measures should be used where possible and countermeasures or mitigation where not. Planning, communication, and assessment provide the basic concepts of managing change (Hallock, 2006).

- Frame the complexity and scope of the project through initial planning and formation of processes and procedures
- Form the contract to communicate how to build the project rather than how to defend the contract
- Conduct a thorough risk assessment

Informal interviews of the customer indicate a thought pattern that the shipyards overestimate the cost of changes. The same types of discussions with shipyard personnel point out the difficulties determining the true impact, indicating the sense that changes are more often underestimated. In order for all participants truly to understand the change, an accurate assessment is an important first step. The assessment should include the reasons for the change (error, omission, and change in scope), type of change, identification of requestor, and the cost efficiency of the change.

A change management process based on best practices may provide the common ground needed to ensure all parties are on the same page. The results of a study using data collected by the Construction Industry Institution (CII) between 1997 and 2001 provided 14 best practices for use in change management (Hallock, 2006):

1. Provide a formal documented change management process to actively manage change on the project and ensure the principal project participants are familiar with it.
2. Establish a baseline project scope early and freeze changes made against this baseline.
3. Establish design “freezes” and communicate them once designs are complete.
4. Identify and evaluate areas susceptible to change during review of the project design baseline.
5. Evaluate changes on the project against the business drivers and success criteria for the project.
6. Require all changes go through a formal change justification procedure.
7. Require mandatory authorization for change prior to implementation.
8. Ensure timely communication of change information to the proper project personnel.
9. Take proactive measures to promptly reconcile, authorize, and execute change orders on the project.
10. Address criteria for classifying change, authorizing change, including the personnel allowed to request and approve, and the basis for adjusting the contract.
11. Set a tolerance level for changes established and communicate it to all project personnel.
12. Process all changes through one owner representative.
13. Evaluate changes made and their impact on cost and schedule at project close-out. Identify lessons learned.
14. Prior to total budget authorization, organize the project in a Work Breakdown Structure (WBS) format, with quantities assigned to each WBS for control purposes.

The change management process should facilitate the orderly and timely processing of justifiable changes. At the same time, unnecessary and/or unjustified change should be both, discouraged and prevented.

a. Change Prevention

Prevention starts with early and frequent communication between the customer and the contractor. Special attention should be given to details as the parties make every effort to understand the requirements. Design reviews should be ongoing throughout the program. With open communication, the reviews should surface areas of uncertainty or concern. These areas of concern should be resolved at the earliest possible time to prevent the compounding affect of instability.

Knowing each party's processes provides insight into why something may be a problem for one and not the other. It also facilitates the lines of communication and understanding required to resolve problems. Analysis of the change, prior to approval, should make every effort to capture all impacts to cost and schedule, including any indirect affects. An accurate, well-justified business case should be included to discourage frivolous change.

b. Change Mitigation

Where change is required, the procedures and process should be in place to prevent as much disruption as possible. This may mean reserving space and weight for systems still under development. The key is understanding each parties processes to determine how best to specify the desire or intent during contract design without tasking the shipbuilder to perform work that will ultimately lead to rework.

For example, if an interface is unknown at the time of contract award, it should be designated as future or reserved. This is as opposed to designating an interface that may change. Without a stop work order, the contractor is obligated to move forward with information that is provided contractually, even if the information is stamped Preliminary. This may mean the purchase of equipment and cables that are never used, or worse, install and ultimately rip-out, for replacement, of the correct equipment and cables.

2. Schedule Flexibility

How is flexibility added to a schedule constrained by a delivery date, competing with the obsolescence of technology? Shipyard build schedules optimize the available workforce and capital costs within the constraints of the acquisition milestones. The schedules try to provide on-time delivery, at the lowest cost, without disrupting other projects. As in any complex schedule, there is available slack time throughout.

Initially, the design change absorbs the available slack in the schedule. The effects are essentially a greedy heuristic where slack is absorbed in a best-fit fashion without full optimization. This is a case where optimizing the parts will not necessarily optimize the whole. The scheduled slack time on the critical path, however, is minimal. As design change absorbs available slack, the critical path starts to lose progress. Depleting non-critical path slack incurs additional cost. However, critical path slack and time are much more costly to consume. Once the critical path is violated, cost grows quickly.

Programs Managers and shipyards should make improving schedule flexibility a priority. Instead of optimizing for economy over the available time, the schedule should include an approach to slack that provides greater resilience to design change impacts. The shipyards need yard specific schedules, using historical data, developed with modern linear programming analysis. This type of built-in resilience encompasses all aspects of ship scheduling to include build strategies and producibility.

At the acquisition level, PMs must account for the effects of design change on the schedule. By directing the shipyard to optimize for flexibility, within reason, the PM acknowledges the need to provide available program time to accommodate potential changes. Program milestones define the bracket within which the ship schedule is executed. Therefore, the program should provide for the additional schedule time needed to optimize the slack time for resilience. This approach provides a greater ability to absorb design change without traumatic impacts to the schedule.

3. Accommodating Technology Insertion

Section 4.4.1 of the Defense Acquisition Guidebook defines an open system as a system that employs modular design principle that “uses widely supported and consensus-based standards for its key interfaces” (DoDD 5000.1, 2003). It further defines “an open systems design as a design approach for developing an affordable and adaptable open system” and suggests that the open systems approach should be applied as part of the program acquisition overall technical approach (DoDD 5000.1, 2003).

Modular Open Systems Approach (MOSA), as identified in section 2.3.15 of the Defense Acquisition Guidebook, is the DoD implementation of open systems (DoDD 5000.1, 2003) and is recommended for inclusion into the acquisition strategy to ensure “access to the latest technologies and products, and to facilitate affordable and supportable system development and modernization of fielded assets” (DoDD 5000.1, 2003).

MOSA is a strategy for effectively developing new systems or modernizing existing ones. It provides a tool that allows members of the acquisition community to design for affordable change, use evolutionary acquisition and spiral development, and develop an integrated roadmap for weapons systems design development (MOSA, 2004). The goals of MOSA is to reduce acquisition cycle time, reuse and standardization of system components, leverage of commercial products, and the ability to insert “cutting edge technology as it evolves” (MOSA, 2004).

MOSA consists of five basic principles employed to help realize benefits of open system design and lay the foundation for identification of gauges that could, and should, be used in acquisition programs. These basic principles are outlined below:

Principle 1: Establish an Enabling Environment – To achieve this objective, all aspects of the acquisition process must be defined and structured to support development of an open system with controls in place to ensure proper implementation (MOSA, 2004).

Principle 2: Employ Modular Design – During the design process, a system must be divided into functional components to make it easier to develop, maintain, modify or upgrade. To achieve this goal the design process must begin with a modular approach with the idea of future evolution in mind (MOSA, 2004).

Principle 3: Designate Key Interfaces – It would not be feasible to attempt to manage every interface of a system. Instead, MOSA seeks to group interfaces into key and non-key interfaces in an effort to utilize open standards for key interfaces where possible (MOSA, 2004).

Principle 4: Use Open Standards – In order to take advantage of modular design and ensure ease of future system changes, “interface standards must be well defined, matured, widely used, and readily available”. Selection of standards should be base on maturity level, acceptance, and allowance for future technology insertion (MOA, 2004).

Principle 5: Certify Conformance – Verification and Validation processes should be in place to ensure conformance to open interfaces that allow “plug and play” of system modules. They should also ensure that component selection avoids use of vendor unique solutions to interface standards (MOA, 2004).

Adherence to these basic principles ensures that a system has access to the latest technology and is easily modifiable and upgradeable to meet future needs. An open system design strategy should be an integral part of the Systems Engineering Process. If all attempts to prevent design changes fail, the shipyard must plan better to accommodate it. Considering that ship design and construction activities are continuing, the primary concern should be to expedite implementation of the change. A method for determining the probability of approval should be established.

Changes involving complex systems have the potential to impact several seemingly unrelated areas. Analysis identifying highly probable changes should result in an immediate stop work order to prevent waste and rework where possible. All potential impacts should be identified in this process. The inter-dependencies may be elusive to the engineer generating the stop work. Missed impacts are almost guaranteed.

4. Future Research

Several potential research subjects present themselves in this area of study. It is a complex and challenging issue. Suggestions for future research include:

- Decomposition, conversion, and linking of performance requirements to ship specifications
- Evaluating design maturity at Critical Design Reviews
- Modifying ship construction schedules to improve slack performance for change management
- Improving modularity and reducing density for new naval ships

With the exception of construction scheduling, all of the suggested subjects relate to systems engineering. Most of the issues in design change and rework can be traced to systems engineering performance, or lack thereof.

E. SUMMARY

The difficulty of design change leading to out-of-sequence work is not new, nor is it exclusive to the shipbuilding industry. Over the past 15 years, many studies were conducted to assess just about every aspect of the acquisition process. DoD has adopted many recommendations and yet programs continue to rush to production with unstable designs, ambiguous or unrealistic requirements, and immature technologies.

The thesis research consistently documents that failure to identify and address technical problems and/or provide realistic cost estimates will ultimately lead to substantial schedule delays and cost overruns. Three critical knowledge points provide direction in achieving a successful outcome. The PM must ensure the criteria for answering these knowledge points is met.

The first critical knowledge point relates to requirements and resources. The thesis research demonstrates the importance of capturing customer requirements and ensuring resources are available to achieve program goals. Requirements must be derived from mature and proven technology. Additionally best practices identified by the GAO

shows that technology development must be conducted separately from product development. This approach reduces program risk and allows for smooth transition between program phases. Finally, enough time and funding must be allocated for successful program execution.

The second critical knowledge point ensures the design is capable of meeting customer requirements. The design must be stable with a mature technology level prior to production. Critical design reviews are performed to ensure the design meets customer requirements. Design maturity and technical risk should be assessed during design review for all system components. Consensus on design readiness, by all stakeholders, should be achieved prior to proceeding to the demonstration phase.

The third knowledge point ensures that the system can be built within cost and schedule prior to manufacturing. Identifying key systems and critical manufacturing processes can influence the system's outcome. Controls should be in place to identify gaps in the manufacturing process and correct or improve process prior to production.

The thesis research illustrates the importance of understanding the design and manufacturing processes. Identifying and addressing technical issues early minimizes the impact of change on cost and schedule. The complexity and interdependencies can be managed with great attention to detail. Failure to address problems early in the process results in issues that cascade and grow throughout the development and production phase. Issues include increased cost, schedule delays, decreased performance, decreased quality, and low employee morale.

The first step in reversing the trend of inherent rework and out-of-sequence work is to enforce existing DoD acquisition policies and hold leadership accountable for their proper execution. In addition, DoD must take a holistic approach and develop an investment strategy that supports the overall goals of U.S. Defense. This begins by developing strategic investment strategies and providing sound business cases for programs that aim to achieve strategic goals.

The next step is to mandate an event driven process as opposed to a schedule driven process. Strict evaluation criteria must be in place to ensure dependent events are

met prior to proceeding to the next phase. This includes requirements for a Technology Maturity Level of 7 or greater for systems and sub-systems under consideration, prior to detail design.

Finally, adequate funding must be provided at inception to support approved programs. Program managers must be empowered in a manner that allows successful execution of the program. With empowerment comes accountability. Program managers must be held accountable for cost, performance, and schedule.

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LIST OF REFERENCES

A Modular Open Systems Approach to Acquisition. (2004). *The Defense Acquisition System*. Washington, DC: Government Printing Office. Retrieved August 26, 2007, from http://www.acq.osd.mil/osjtf/pdf/pmg_section1.pdf.

Arena, M.V., Birkler, J., Schank, J.F., Riposo, J., & Grammich, C.A. (2005). *Monitoring the Progress of Shipbuilding Programs: How Can the Defense Procurement Agency More Accurately Monitor Progress*. Santa Monica, CA: Rand. Retrieved December 30, 2006, from http://www.rand.org/pubs/monographs/2005/RAND_MG235.pdf.

Arena, M.V., Blickstein, I., Younossi, O., & Grammich, C.A. (2006). *Why Has the Cost of Navy Ships Risen? A Macroscopic Examination of the Trends in U.S. Naval Ship Costs Over the Past Several Decades*. Santa Monica, CA: Rand. Retrieved December 30, 2006 from <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA449271&Location=U2&doc=GetTRDoc.pdf>.

Blickstein, I. & Smith, G. (2002). A Preliminary Analysis of Advance Appropriations as a Budgeting Method for Navy Ship Procurements. Santa Monica, CA: Rand. Retrieved December 30, 2006 from http://www.rand.org/pubs/monograph_reports/2005/MR1527.pdf.

Castelli, C. (2006, January 19). Navy Shipbuilding Plan Called Unrealistic. InsideDefense.com NewsStand. Retrieved December 16, 2006 from <http://www.military.com/features/0,15240,85654,00.html>.

CRS Report for Congress. (2005). *Navy Ship Acquisition: Options for Lower-Cost Ship Designs —Issues for Congress*, (RL32914). Congressional Research Service – The Library of Congress. Retrieved November 8, 2006 from <http://www.fas.org/sgp/crs/weapons/RL32914.pdf>.

Defense Acquisition Guidebook. (2006). Retrieved July 10, 2007, from <https://akss.dau.mil/dag/DoD5000.asp?view=document>.

Department of Defense Directive Number 5000.1. (2003). *The Defense Acquisition System*. Washington, DC: Government Printing Office. Retrieved September 21, 2006, from http://www.nmrc.navy.mil/pdf/dodd_5000_1.pdf.

Department of Defense Instruction Number 5000.2. (2003). *Operation of the Defense Acquisition System*. Washington, DC: Government Printing Office. Retrieved September 21, 2006, from http://www.dau.mil/registrar_private/DoDI5000-2-12May03.pdf.

Earl, C., Eckert, C., & Clarkson, J. (2005). *Design Change and Complexity. Proceedings from the Workshop on Complexity in Design and Engineering*. Glasgow, Scotland, UK, (pp. 24-33). Retrieved November 11, 2006 from <http://www.dcs.gla.ac.uk/~johnson/complexity/Proceedings/CiD2005.PDF>.

Francis, Paul L. (2007). *Testimony Before the Subcommittee on Seapower and Expeditionary Forces*. Committee on Armed Services, House of Representatives. Washington, DC. [Transcript]. Retrieved August 29, 2007, from http://armedservices.house.gov/hearing_information.shtml.

Hallock, B. (2006). Nielsen-Wurster Communiqué. (Vol. 1.6). *Managing Change vs. Administering the Change Order Process*. Retrieved August 22, 2007, from http://www.nielsen-wurster.com/Email_Announcements/NW_Communique/PDF's/v%201-6%20December%202006.pdf.

Howard, J.E. & Collins, P.B. (2005). Cost Benefit Analysis of Government Furnished Equipment versus Contract Furnished Equipment for the Procurement and Integration of the MK-44 Chain Gun with the United States Marine Corps Expeditionary Fighting Vehicle (Thesis: Naval Postgraduate School). Retrieved 12/03/2006 from <http://biblio.nps.edu/uhtbin/cgisirsi.exe/6g0TIIxkDo/x/284250018/524/7814>.

Johnson, C. (2005). *What are Emergent Properties and How Do They Affect the Engineering of Complex Systems? Proceedings from the Workshop on Complexity in Design and Engineering*. Glasgow, Scotland, UK, (pp. 8-19). Retrieved November 11, 2006 from <http://www.dcs.gla.ac.uk/~johnson/complexity/Proceedings/CiD2005.PDF>.

Jones, B.S. & Anderson, P. (2005). *Diversity as a Determinant of System Complexity. Proceedings from the Workshop on Complexity in Design and Engineering*. Glasgow, Scotland, UK, (pp. 38-45). Retrieved November 11, 2006 from <http://www.dcs.gla.ac.uk/~johnson/complexity/Proceedings/CiD2005.PDF>.

Kanerva, M., Lietepohja, M., & Hakulinen, P. (2002). Shipbuilding Process – Challenges and Opportunities: An IBM Product Lifecycle Management Resource Paper. Retrieved December 16, 2006 from <http://www-03.ibm.com/solutions/plm/doc/content/bin/shipbuilding.pdf>.

Keane, R.G. Jr., Fireman, H., & Billingsley, D.W. (2005) *Leading a Sea Change in Naval Ship Design: Toward Collaborative Product Development. Proceedings from the 2005 SNAME Maritime Technology Conference & Expo and Ship Production Symposium*. Houston, TX. Retrieved October 13, 2006 from <http://www.nnapprentice.com/sname/letter/Leading%20a%20Change%20in%20Naval%20Ship%20Design%20Toward%20Collaborative%20Product%20Development.pdf>.

Keane, R.G. Jr. & Fireman, H. (1992). *Producibility in the Naval Ship Design Process: A Progress Report Naval. Proceedings of the Ship Production Symposium*. New Orleans, LA. Retrieved October 13, 2006 from <http://handle.dtic.mil/100.2/ADP023033>.

Keller, R., Eckert, C.M., & Clarkson, P.J. (2005). *Viewpoints and Views in Engineering Change Management. Proceedings from the Workshop on Complexity in Design and Engineering*. Glasgow, Scotland, UK, (pp. 188-192.). Retrieved November 11, 2006 from <http://www.dcs.gla.ac.uk/~johnson/complexity/Proceedings/CiD2005.PDF>.

Maiden, N. & Jones, S. (2005). *Creativity in the Design of Complex Systems. Proceedings from the Workshop on Complexity in Design and Engineering, Glasgow, Scotland, UK*, (pp. 34-37). Retrieved November 11, 2006 from <http://www.dcs.gla.ac.uk/~johnson/complexity/Proceedings/CiD2005.PDF>.

Marashi, E. & Davis, J. P. (2005). A Systems Approach to Resolving Complex Issues in a Design Process. *Proceedings from the Workshop on Complexity in Design and Engineering*. Glasgow, Scotland, UK, (pp. 160-169). <http://www.dcs.gla.ac.uk/~johnson/complexity/Proceedings/iD2005.PDF>.

Moosally, F.P., Moak, K., McCreary, R., & Ellis, M. (2007). *Statement of Fred P. Moosally, President, Lockheed Martin MS2, Kevin Moak, Chairman & President, Gibbs & Cox, Richard McCreary, Vice President & General Manager, Marinette Marine Corporation, Mike Ellis, Executive Vice President & Chief Operating Officer, Bollinger Shipyards, Inc., Before the House Armed Services Committee, Subcommittee on Seapower and Expeditionary Forces*. Retrieved July 12, 2007, from, http://armedservices.house.gov/pdfs/SPEF_LCS020807/Industry_Testimony020807.pdf.

Moyst, H. (2001). *Optimizing the Integration of Ship Design with Construction: A Linear Programming Approach*. (Thesis: Dalhousie University). Retrieved 10//13/2006 from <http://www.clelections.ca/obj/s4/f2/dsk3/ftp05/MQ63541.pdf>.

Naval Surface Warfare Center (1985). *Design for Production Manual. Volume 1. Design/Production Integration (CD Code 2230)*. Bethesda, MD: SNAME Retrieved December 5, 2006 from <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA454574&Location=U2&doc=GetTRDoc.pdf>.

Naval Surface Warfare Center (1985). *Design for Production Manual. Volume 2. Design/Production Integration (CD Code 2230)*. Bethesda, MD: SNAME Retrieved December 5, 2006 from <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA445624&Location=U2&doc=GetTRDoc.pdf>.

Naval Surface Warfare Center (1985). *Design for Production Manual. Volume 3. The Application of Production Engineering (CD Code 2230)*. Bethesda, MD: SNAME Retrieved December 5, 2006 from <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA454575&Location=U2&doc=GetTRDoc.pdf>.

Naval Surface Warfare Center (1983). *The National Ship Building Program: Design for Zone Outfitting. (CD Code 2230)*. Bethesda, MD: NSRP Retrieved December 5, 2006 from <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA452731&Location=U2&doc=GetTRDoc.pdf>.

Office of the Deputy Director of Defense Procurement for Cost, Pricing, and Finance (DP/CPF). (2000). *Contract Pricing Reference Guides* (Vols 1-5). Retrieved July 28, 2007, from <http://www.acq.osd.mil/dpap/contractpricing/about.htm>.

Office of the Secretary of Defense (OSD). *Defense Budget Materials*. Retrieved August 22, 2007, from <http://www.defenselink.mil/comptroller/defbudget/fy2008/index.html>.

Office of the Under Secretary of Defense for Acquisition. (1993). *Engineering in the Manufacturing Process, Defense Science Board Task Force Report*. Retrieved November 11, 2006 from <http://www.acq.osd.mil/dsb/reports/engineeringmanufacturing.pdf>.

Plato. (c1985). *The Republic* (R. Sterling, W. Scott, Trans.). New York: Norton. Retrieved August 28, 2007, from the Internet Classics Archive site: <http://classics.mit.edu/Plato/republic.3.ii.html>.

Shenoi, R.A. (2006). Part II Ship Production Technology. School of Engineering Sciences Web site. Retrieved June 28, 2007, from http://www.sesnet.soton.ac.uk/degpro/SESS2002/SESS2002_lecture_notes.htm.

Storch, R.L., Hammon, C.P., Bunch, H.M., & Moore, R.C. (1995). *Ship Production* (2nd ed.). Centreville: Cornell Maritime.

Teel, P.A., (2007). *Statement for the Record, Mr. Phillip A. Teel, Corporate Vice President, Northrop Grumman Corporation, and President, Northrop Grumman Ship Systems, Inc., Testimony Before the House Armed Services Committee, Subcommittee on Seapower and Expeditionary Forces*. Retrieved July 12, 2007, from, http://armedservices.house.gov/pdfs/SPEF032007/Teel_Testimony032007.pdf.

The Society of Naval Architects and Marine Engineers. (1980). *Ship Design and Construction*. New York: Author.

Todd Shipyards Corporation. (1986). The National Shipbuilding Research Program. Product Work Classification and Coding. DTIC Public STINET Web site. Retrieved July 5, 2007, from <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA454578&Location=U2&doc=GetTRDoc.pdf>.

Transforming the Navy's Surface Combatant Force, (2003, March), Washington DC: Congressional Budget Office. Retrieved August 23, 2007 from <http://www.cbo.gov/ftpdoc.cfm?index=4146&type=0>.

United States Department of Defense. (2003). *Operation of the Defense Acquisition System, 5000.2*. Washington, DC: Government Printing Office. Retrieved September 21, 2006, from http://www.address_of_DoD_5000.2.gov.

United States Department of Defense. *Selected Acquisition Summary Tables*. Retrieved August 22, 2007, from <http://www.acq.osd.mil/ara/am/sar/index.html>.

U.S. Department of Transportation Maritime Administration, & Todd Pacific Shipyards Corporation. (1985). The National Shipbuilding Research Program. Process Analysis Via Accuracy Control. DTIC Public STINET Web site. Retrieved June 28, 2007, from <http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA452827&Location=U2&doc=GetTRDoc.pdf>.

United States Government Accountability Office. (2005). *Best Practices Better Support of Weapon System Program Managers Needed to Improve Outcomes* (GAO-06-110). Washington, DC: Government Printing Office. Retrieved July 31, 2007, <http://www.gao.gov/new.items/d06110.pdf>.

United States Government Accountability Office. (2002). *Best Practices Capturing Design and Manufacturing Knowledge Early Improves Acquisition Outcomes* (GAO-02-701). Washington, DC: Government Printing Office. Retrieved August 12, 2007, from <http://www.gao.gov/new.items/d02701.pdf>.

United States Government Accountability Office. (1999). *Better Management of Technology Development Can Improve Weapon System Outcomes* (GAO-99-162). Washington, DC: Government Printing Office. Retrieved July 30, 2007, from <http://www.gao.gov/archive/1999/ns99162.pdf>.

United States Government Accountability Office. (2005). *Defense Acquisitions: Improved Management Practices Could Help Minimize Cost Growth in Navy Shipbuilding Programs* (GAO-05-183). Washington, DC: Government Printing Office. Retrieved December 17, 2006, from <http://www.gao.gov/cgi-bin/getrpt?GAO-05-183>.

United States Government Accountability Office. (2006). *Defense Acquisitions: Major Weapon Systems Continue to Experience Cost and Schedule Problems under DoD's Revised Policy* (GAO-06-368). Washington, DC: Government Printing Office. Retrieved August 7, 2007, from
<http://www.gao.gov/new.items/d06368.pdf>.

United States Government Accountability Office. (2006). *Defense Contracting – Questions for the Record* (GAO-07-217R). Washington, DC: Government Printing Office. Retrieved August 12, 2007, from
<http://www.gao.gov/new.items/d07217r.pdf>.

United States Government Accountability Office. (2007). *Realistic Business Cases Needed to Execute Navy Shipbuilding Programs* (GAO-07-943T). Washington, DC: Government Printing Office. Retrieved August 7, 2007, from
www.gao.gov/new.items/d07943t.pdf.

Wynn, D., Eckert, C., & Clarkson, J. P. (2005). *Abstracting Complexity for Design Planning. Proceedings from the Workshop on Complexity in Design and Engineering*. Glasgow, Scotland, UK, (pp. 20-23), Retrieved November 11, 2006 from <http://www.dcs.gla.ac.uk/~johnson/complexity/Proceedings/CiD2005.PDF>.

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